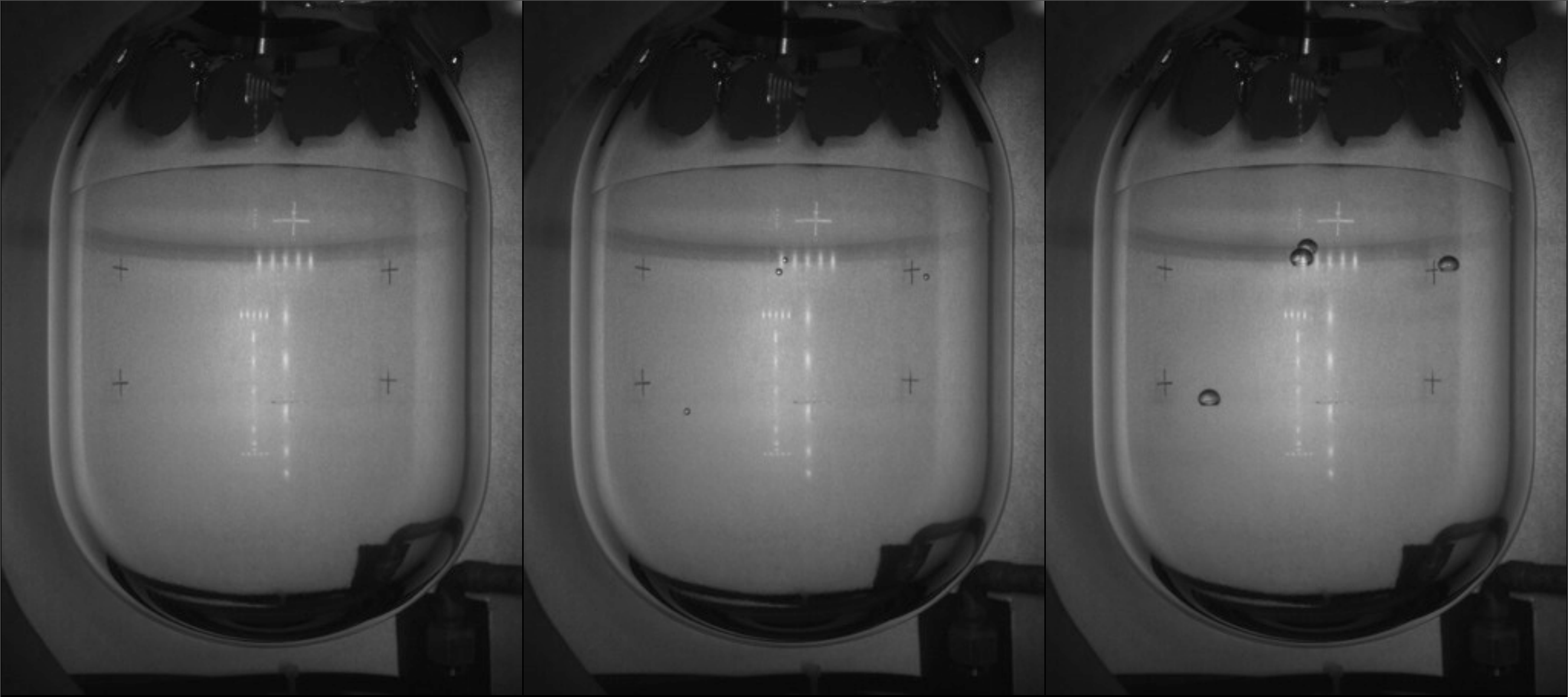


Searching for Dark Matter in a Bubble Chamber

Hugh Lippincott, Fermilab

Seminar at University of California, Davis
April 15, 2013

COUPP Collaboration

M. Ardid[1], E. Behnke[2], T. Benjamin[2], M. Bou-Cabo[1], S.J. Brice[3], D. Broemmelsiek[3], J.I. Collar[4], P.S. Cooper[3], M. Crisler[3], C.E. Dahl[5], E. Grace[2], J. Hall[3], C. Harnish[2], I. Levine[2], W.H. Lippincott[3], D. Maurya[6], T. Nania[2], R. Neilson[4], S. Priya[6], E. Ramberg[3], A.E. Robinson[4], A. Sonnenschein[3], and E. Vázquez Jáuregui[7]

[1]Politecnica Valencia
[2]Indiana University South Bend
[3]Fermi National Accelerator Laboratory
[4]KICP - University of Chicago
[5]Northwestern University
[6]Virginia Tech
[7]SNOLAB

KICP Kavli Institute for Cosmological Physics at the University of Chicago

SNOLAB Mining for knowledge / Creuser pour trouver... l'excellence

Northwestern University

Fermilab

Indiana University South Bend

VirginiaTech

Universitat Politècnica de València

With support from:

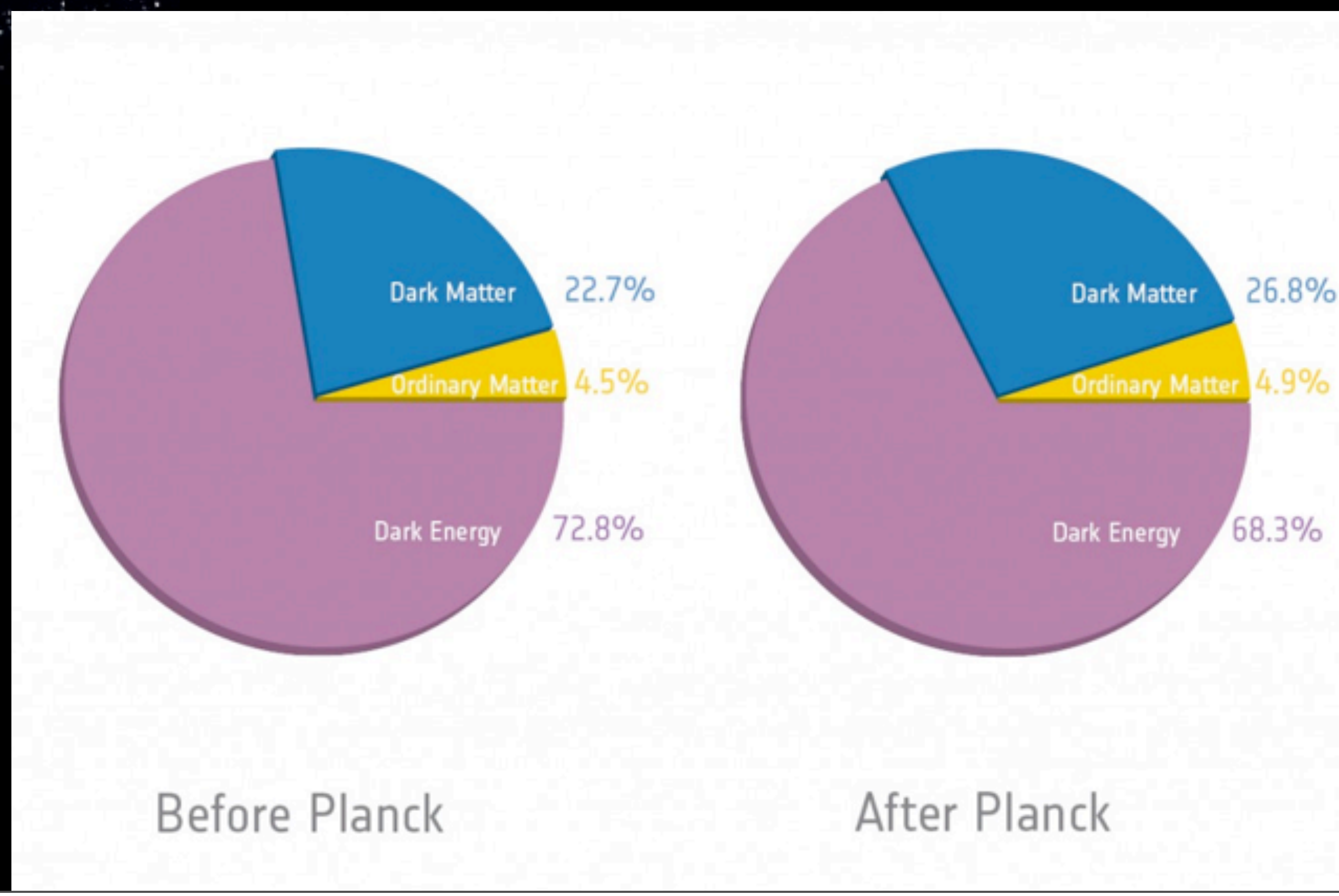
U.S. Department of Energy

NSF

The Kavli Foundation

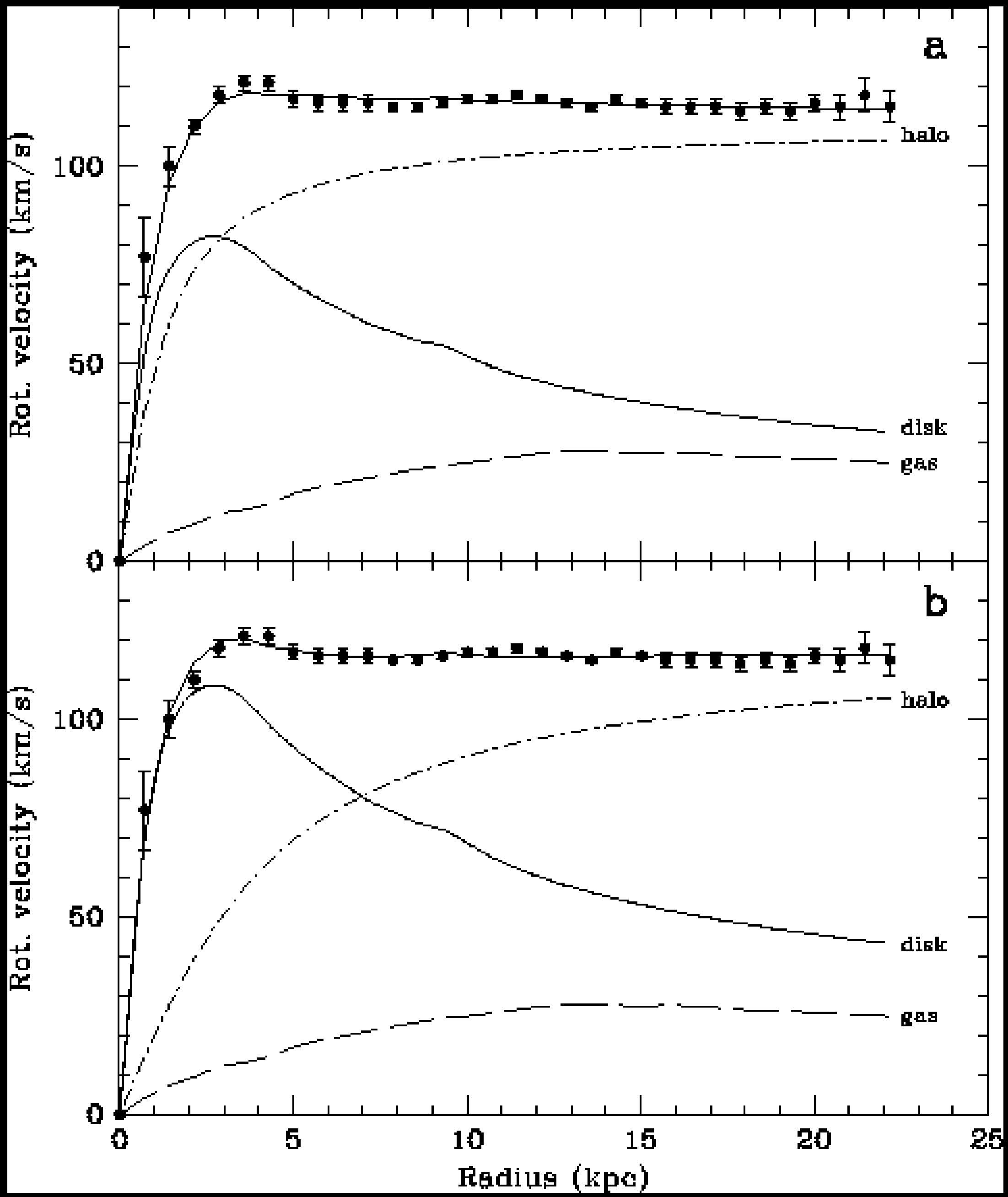
There is pretty strong consensus regarding how much stuff there is in the universe

By that same consensus, we only understand 5% of it



Dark matter - evidence?

- Galaxy rotation curves



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Fritz Zwicky, 1930

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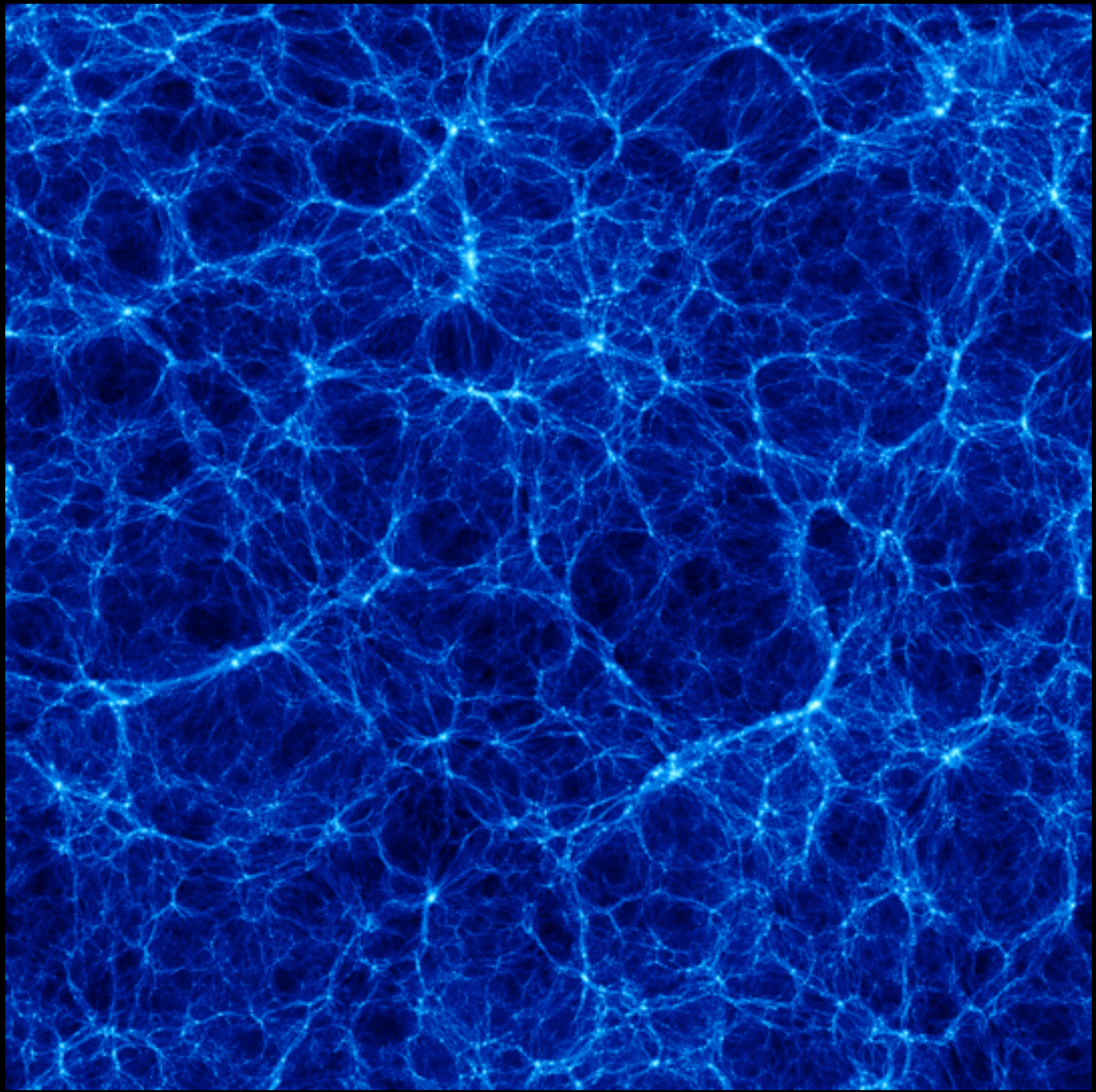

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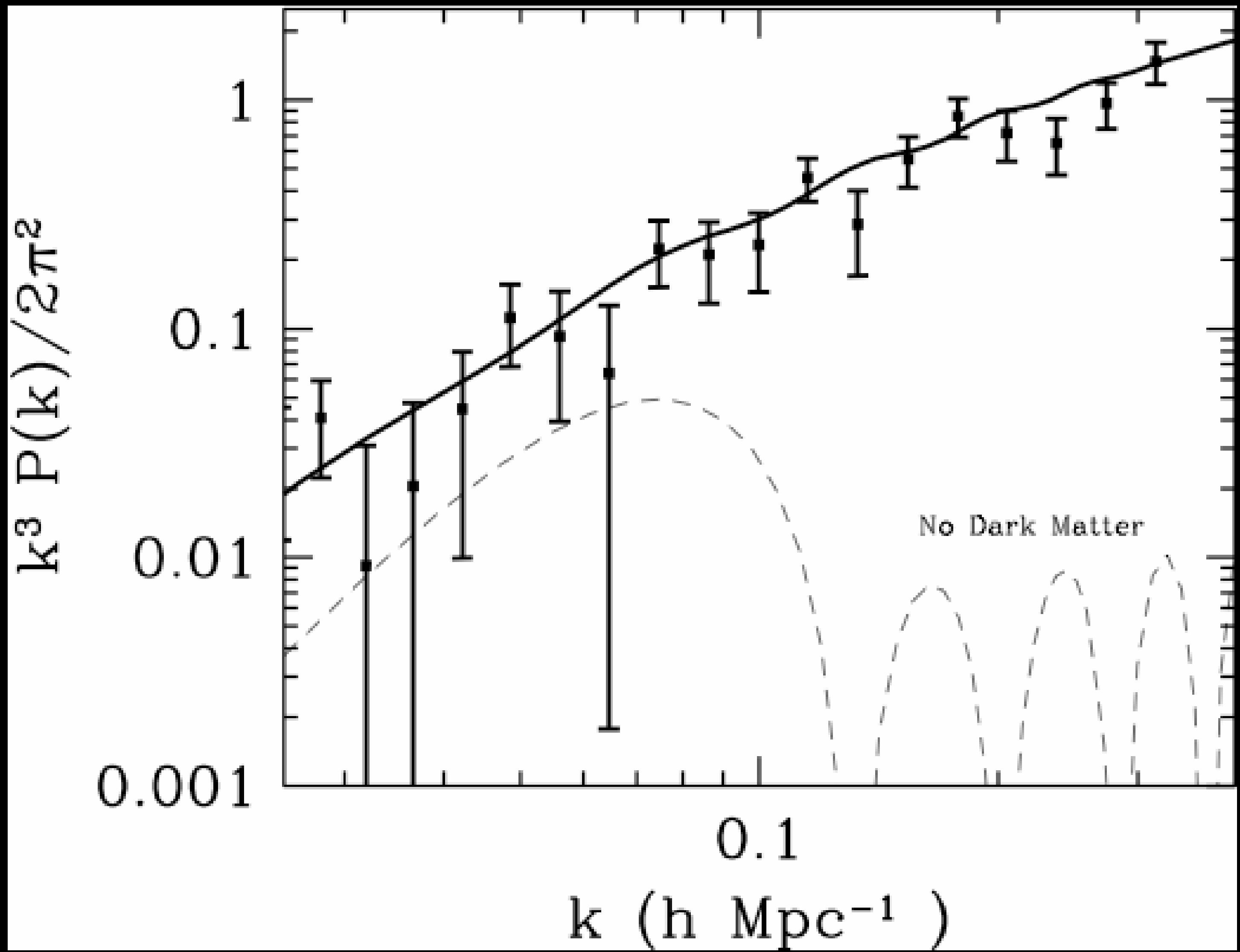

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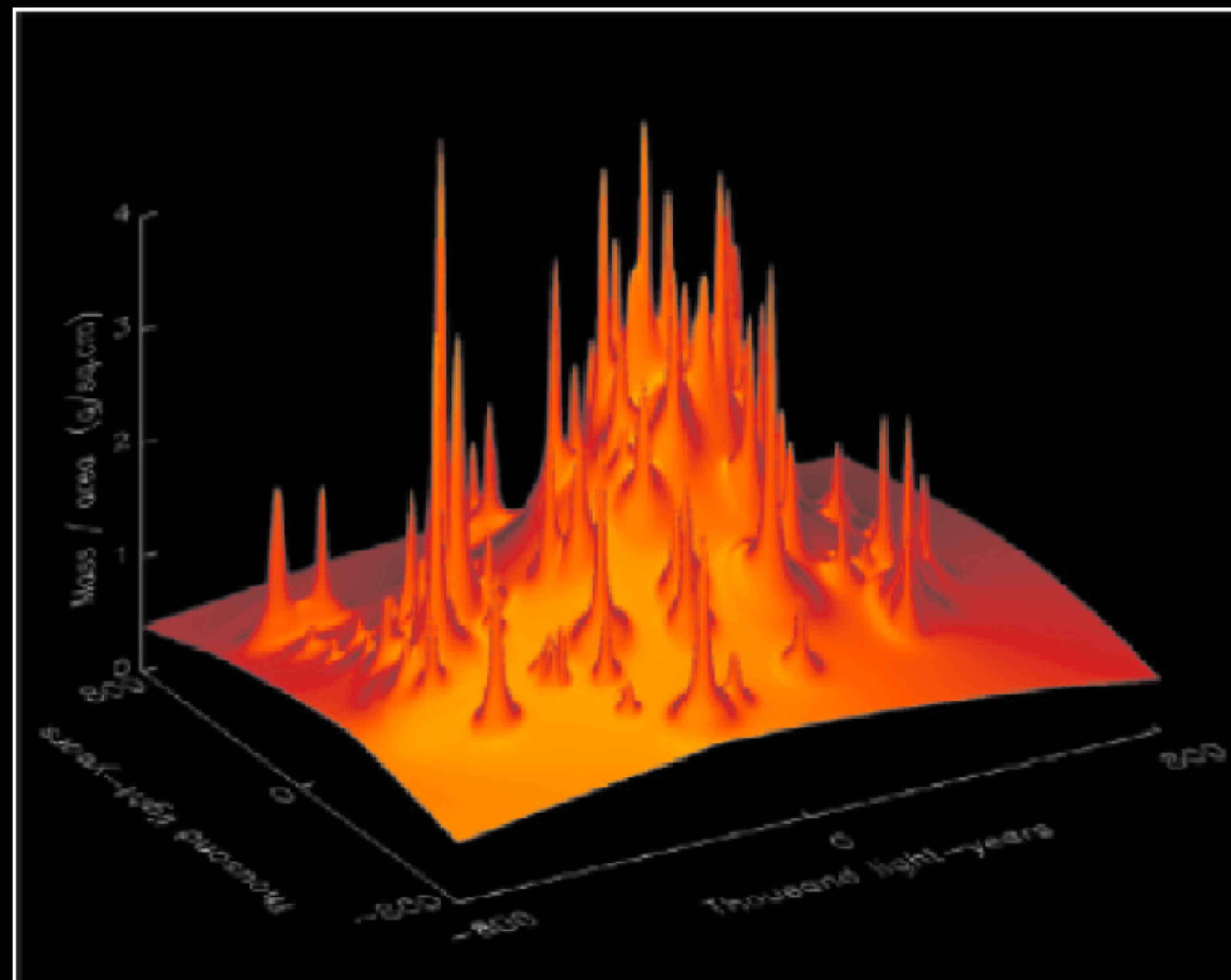

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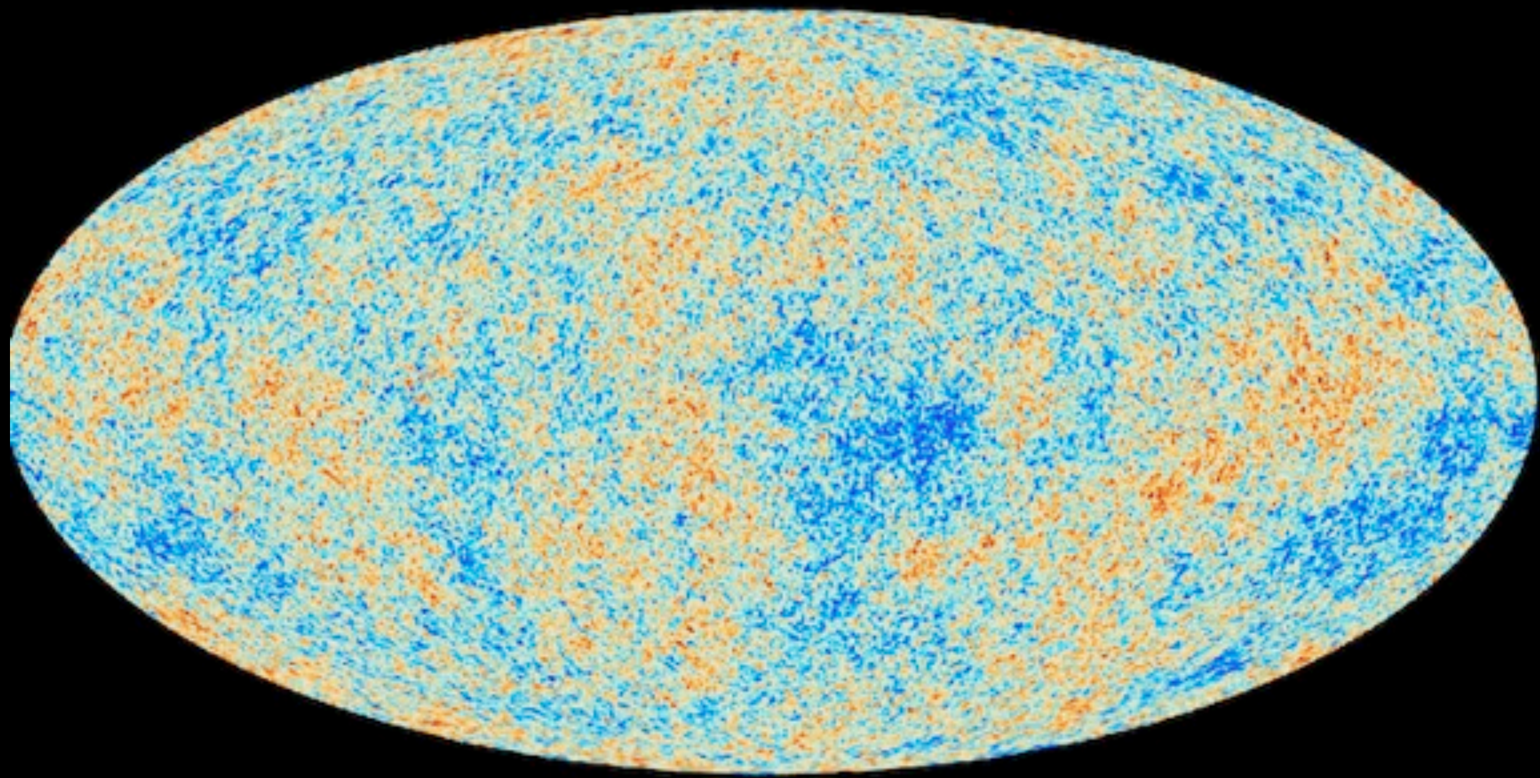

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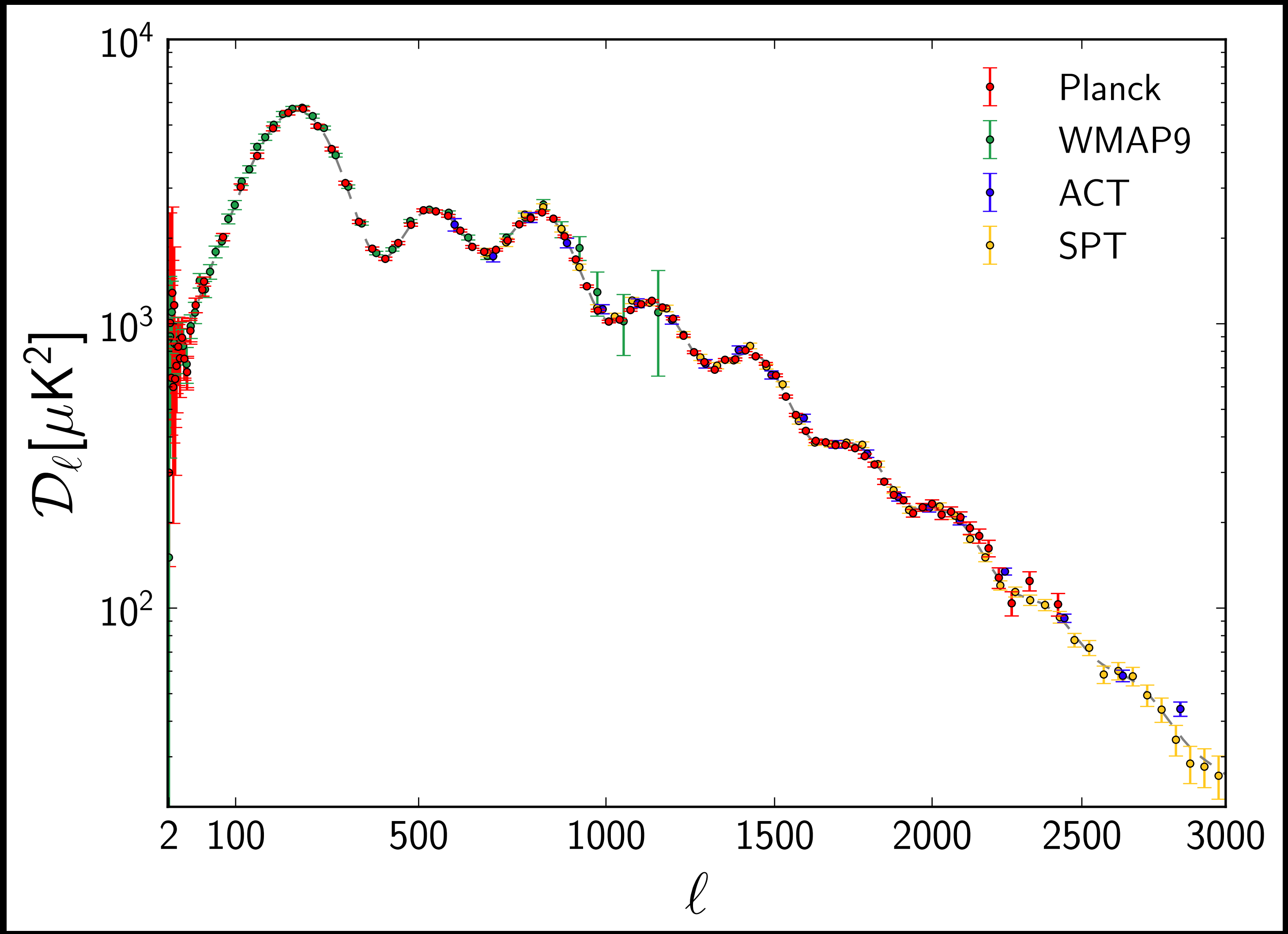

Dark matter - evidence?

- Galaxy rotation curves
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- Gravitational lensing
- Cosmic microwave background
- Galactic collisions

So what is it?

- We know it interacts gravitationally
- It is "dark" - should not interact with light or electromagnetism
- Nearly collisionless
- Slow

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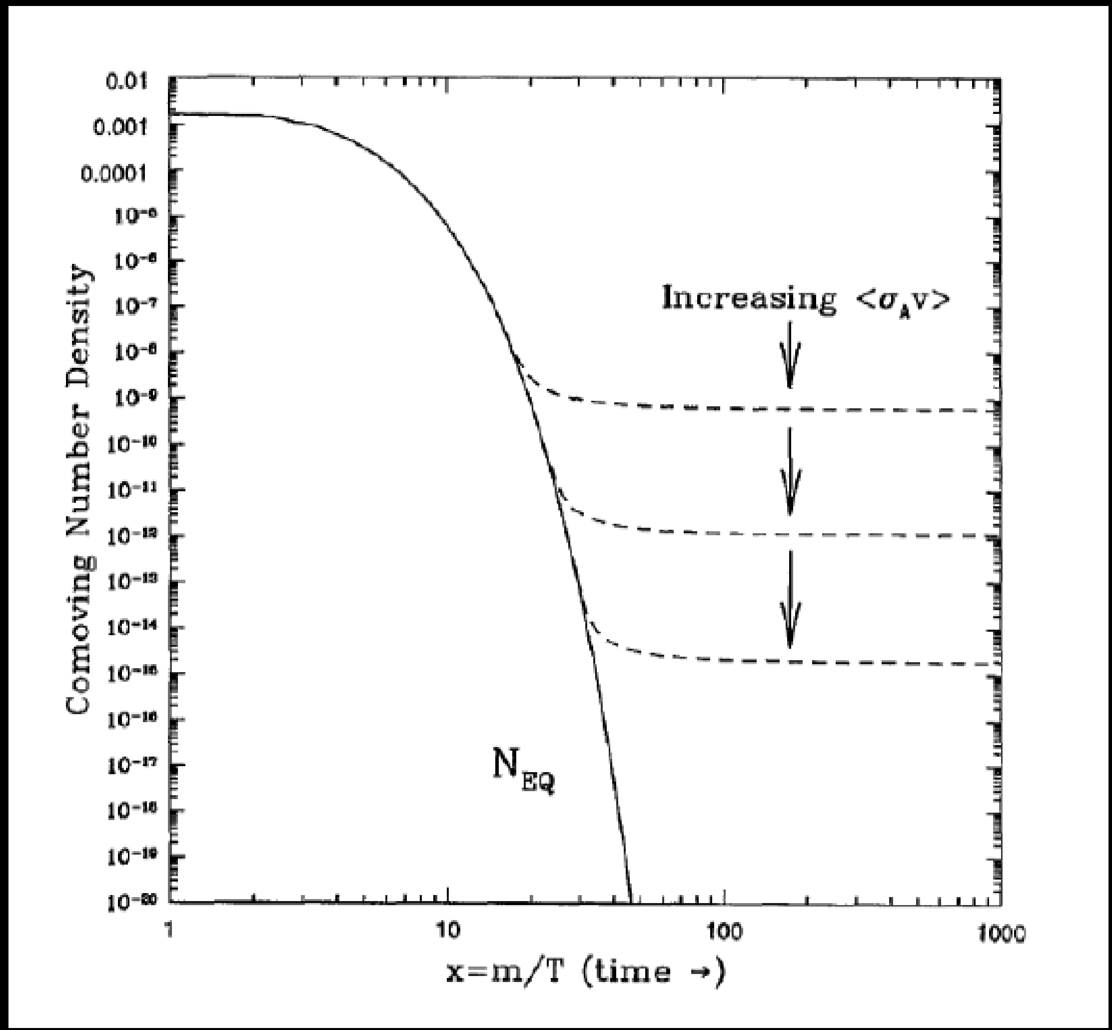
Beyond the Standard Model!

WIMPs

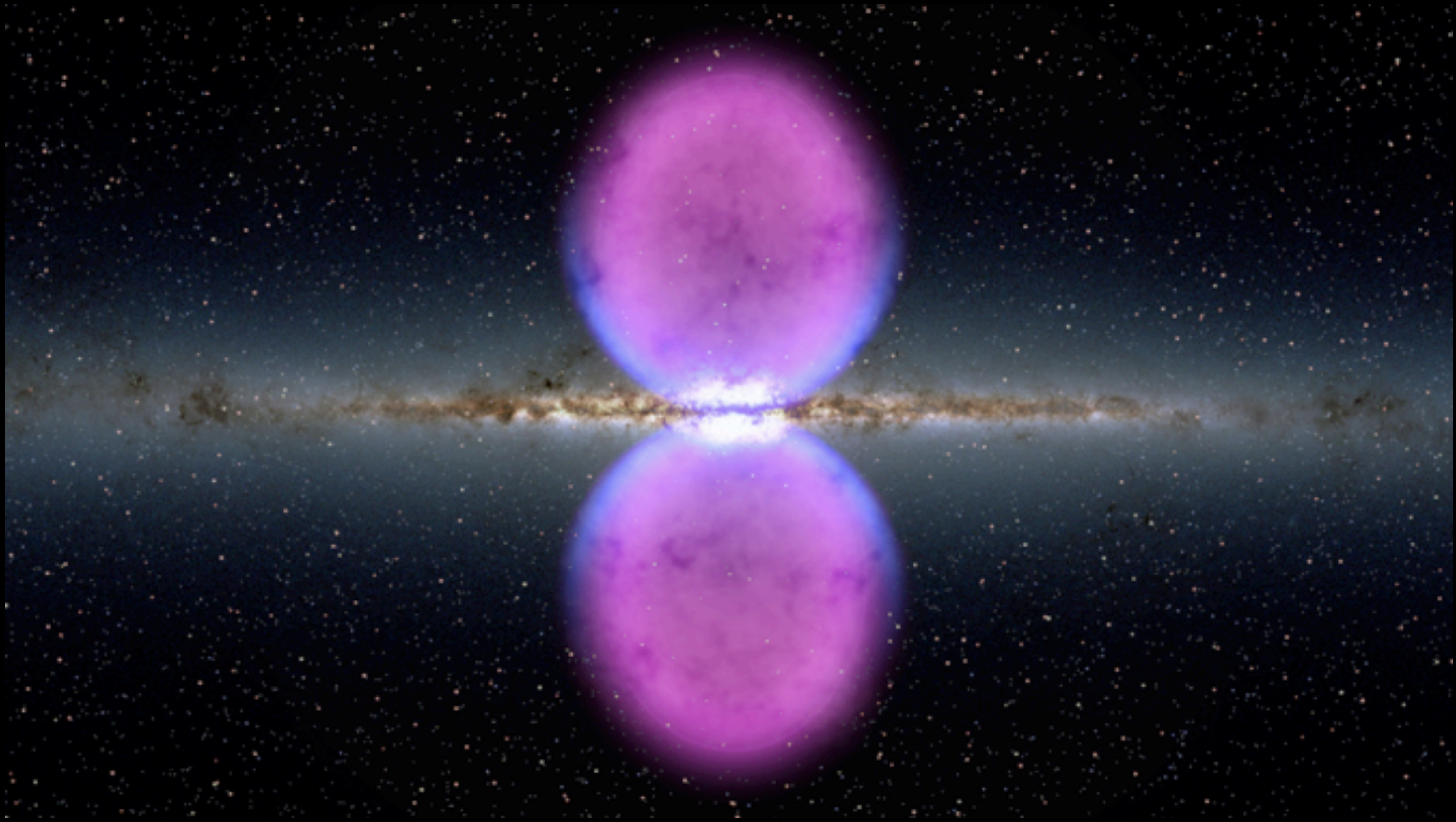
- Most discussed candidate is Weakly Interacting Massive Particle
  - Produced during big bang
  - Decouples from ordinary matter as the universe expands and cools
  - Still around today with densities of about a few per liter



- Supersymmetry produces a theoretical candidate (LSP), but others exist (e.g. Kaluza-Klein particles, ...)

How do we find it?

- Indirect - detect annihilation products from regions of high density like the sun or the center of the galaxy



Fermi bubbles, courtesy of NASA

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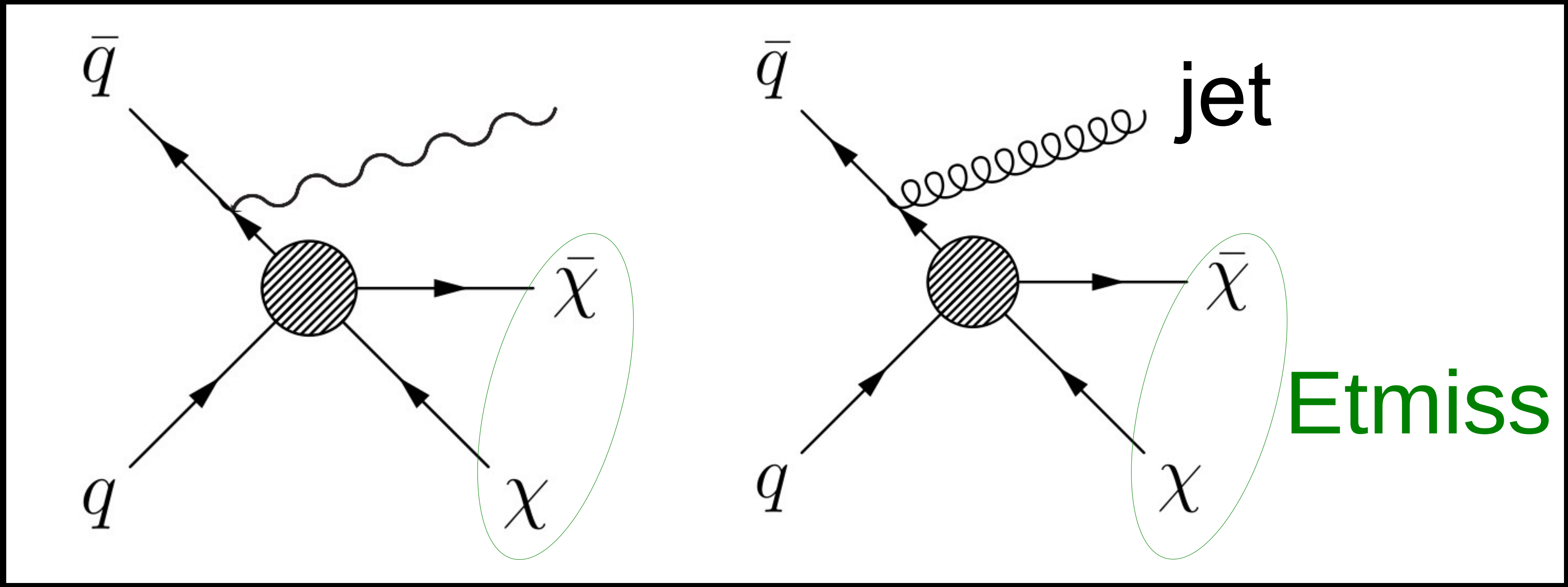
- Accelerators - create a WIMP at the LHC
  - Missing ET and monojet searches



How do we find it?

- Indirect - detect annihilation products from regions of high density like the sun or the center of the galaxy
- Accelerators - create a WIMP at the LHC
  - Missing ET and monojet searches
- Direct detection - WIMPs can scatter elastically with nuclei and the recoil can be detected

$$\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2\mu_p^2} \times F^2(Q) \times \int_{v_m} \frac{f(v)}{v} dv$$

Rate calculation

- The differential cross section (for spin-independent interactions) per kilogram of target mass per unit recoil energy is

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- The velocity distribution of dark matter in the galaxy - of order 30% uncertainty, and $v_m = \sqrt{Q/2m_r^2}$

The energy scale

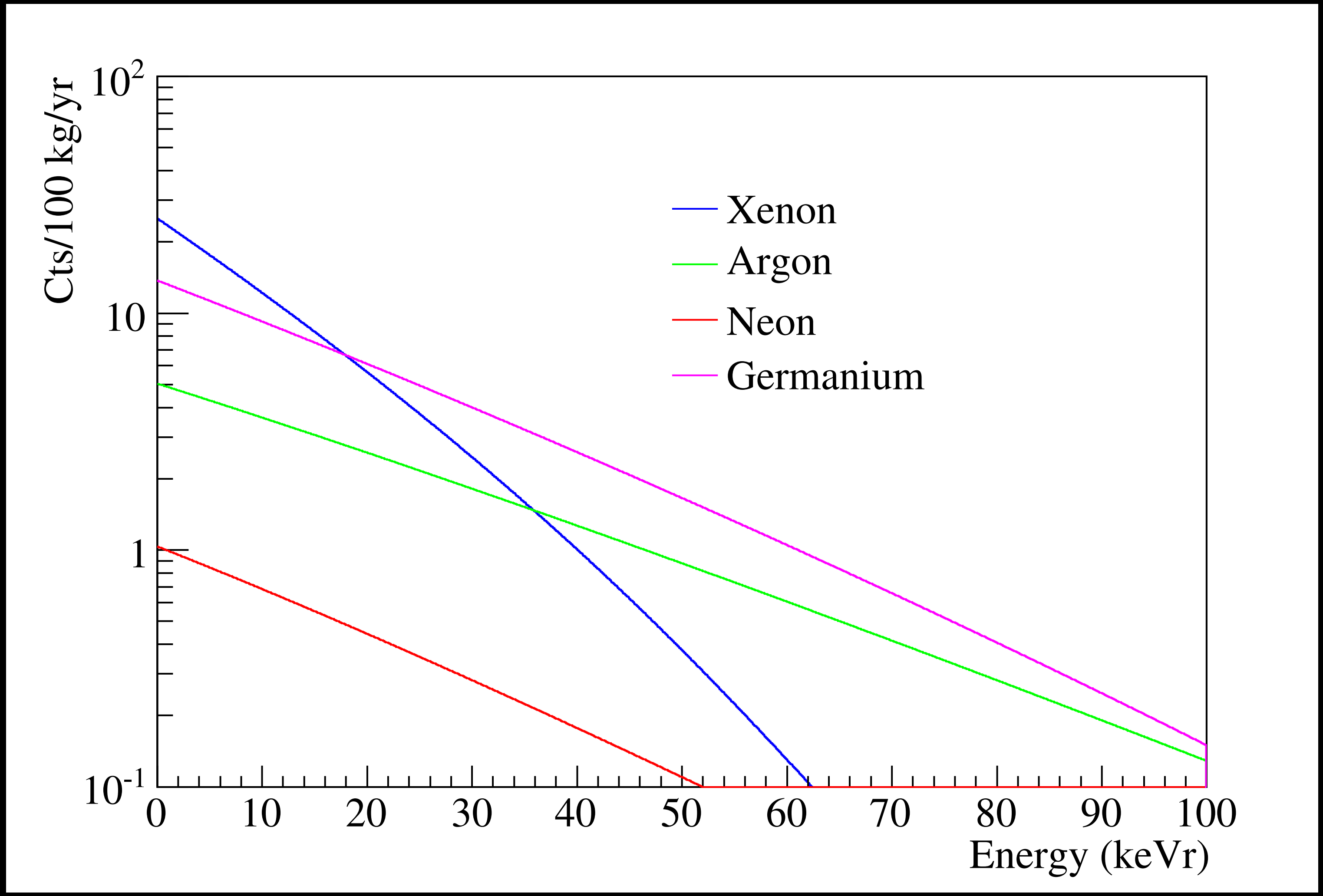
- Energy of recoils is tens of keV
- Entirely driven by kinematics, elastic scattering of things with approximately similar masses (100 GeV) and v ~ 0.001c

$$\frac{1}{2} m_N v_N^2 = \frac{1}{2} \times 100\,\mathrm{GeV} \times 10^{-6} = 50\,\mathrm{keV}$$

Rate calculation

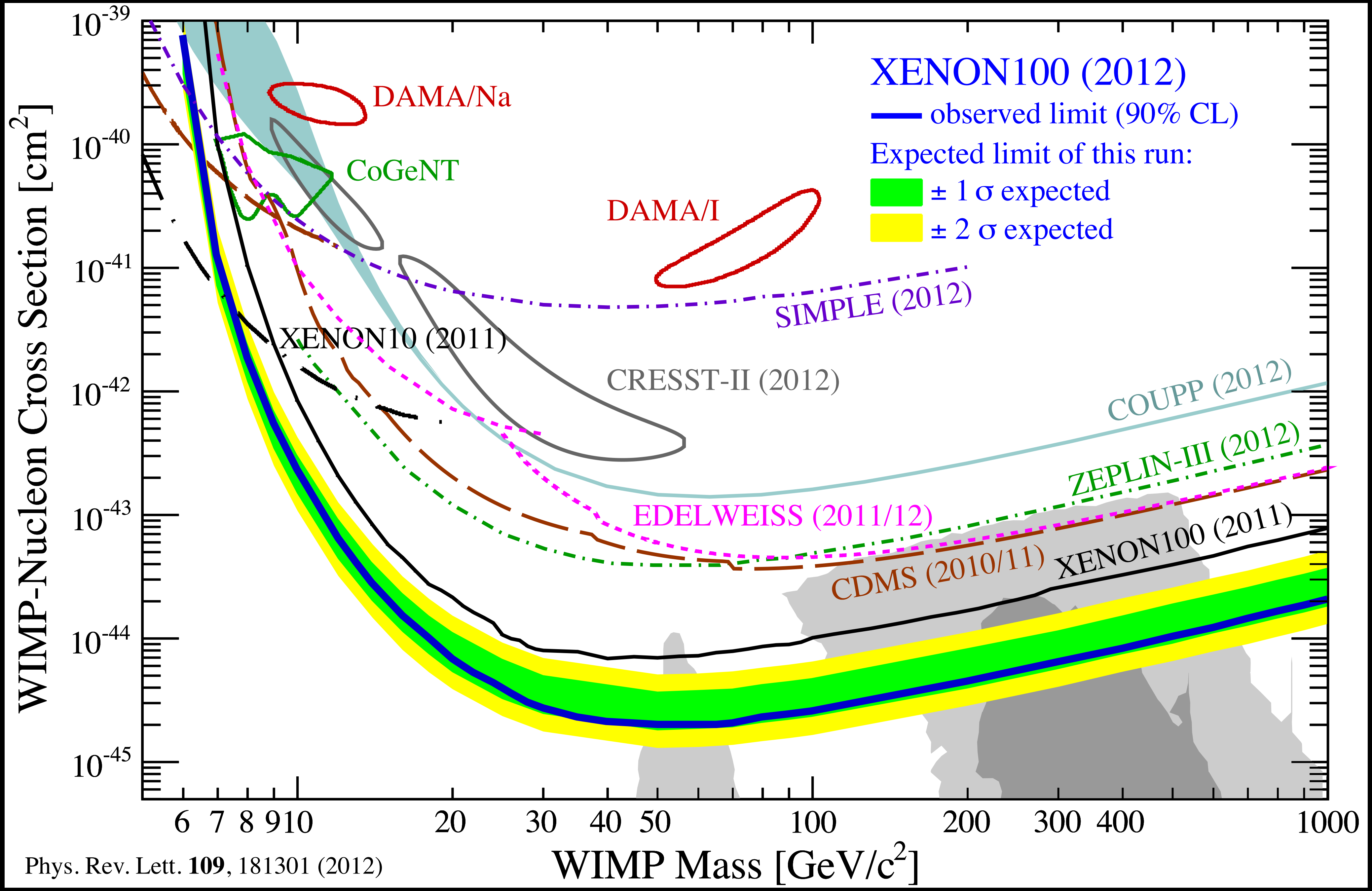
- Integrated rate above threshold, 100 GeV WIMP, $\sigma_0 = 10^{-45}$ cm^2

$$I = \int_{Q_{thresh}} dQ\, dR/dQ = \int_{Q_{thresh}} dQ \frac{\rho_0}{m_\chi} \frac{\sigma_0 A^2}{2\mu_p^2} F^2(Q) \int_{v_m} \frac{f(v)}{v} dv$$



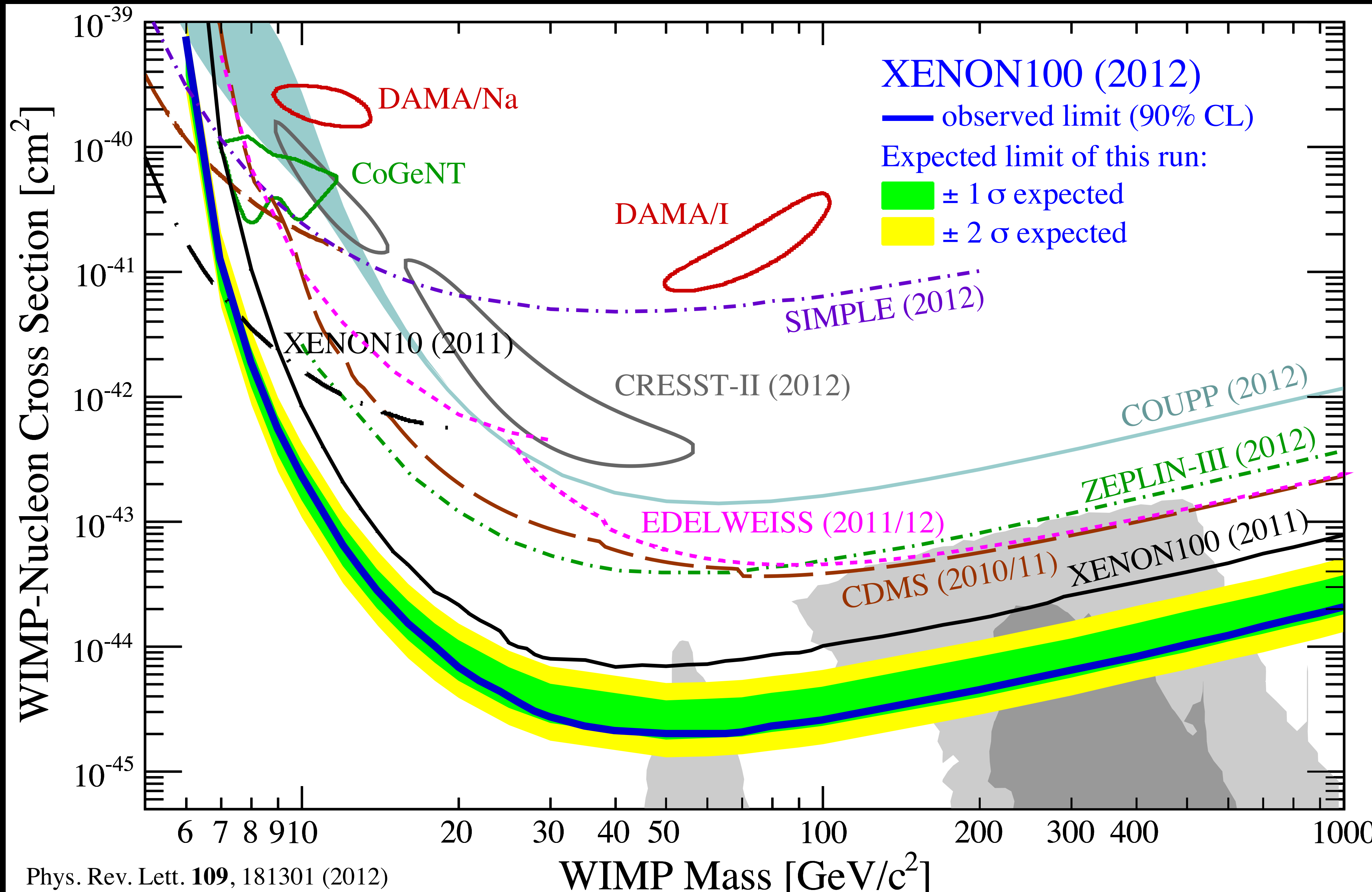
- Looking for a handful of events

The canonical plot



- Limited at low mass by detector threshold
- Limited at high mass by density

The canonical plot



- What happened to "weakly" interacting?
- Mediation via Z was excluded long ago ($\sim 10^{-39}$ cm^2), but only now are we probing Higgs exchange

So we look for WIMPs

- A few hundred just passed through us, and we might expect a handful of counts in a detector per year

So we look for WIMPs

- A few hundred just passed through us, and we might expect a handful of counts in a detector per year
- The problem is that background radioactivity is everywhere!

100 events/second/kg =
3,000,000,000,000 events/year
in a ton-scale experiment

Backgrounds!

Background sources

- Cosmic rays are constantly streaming through
    - All experiments have to go underground to get away from cosmic rays


SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

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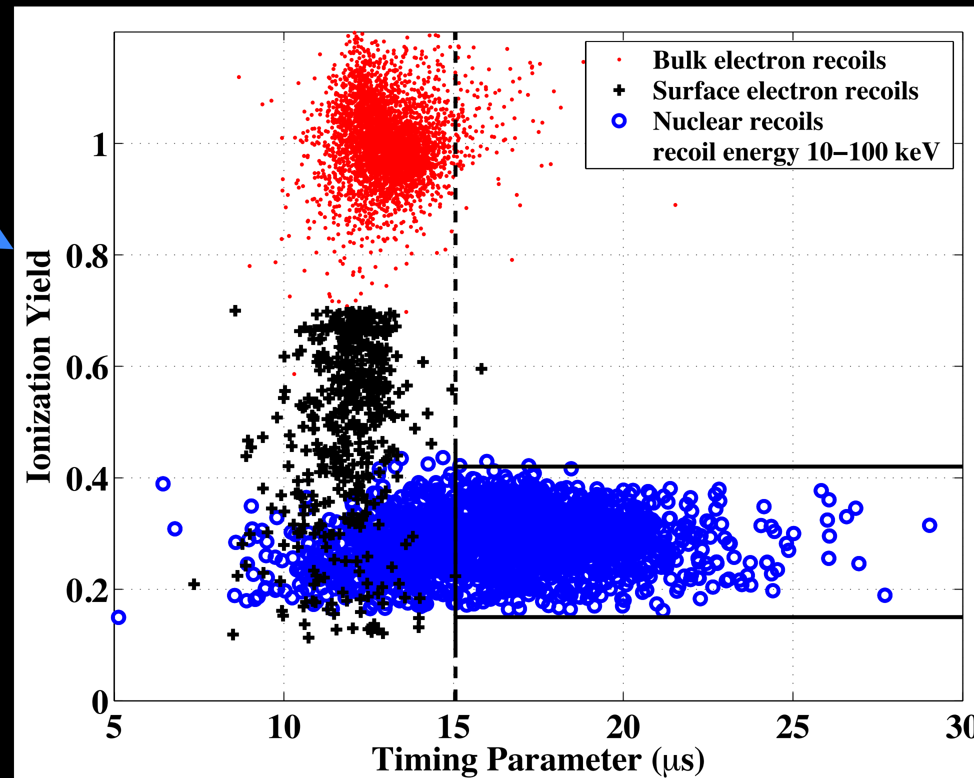
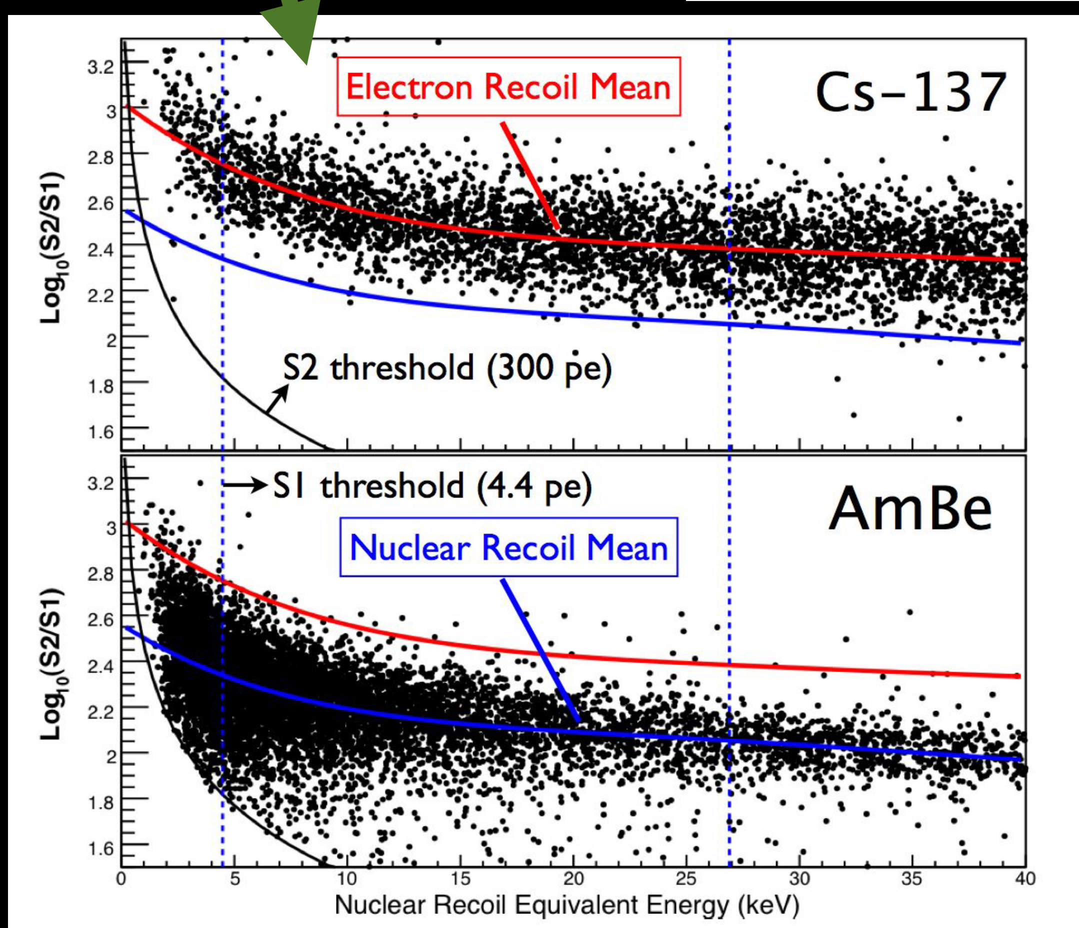
  - Self-shielding to leave a clean inner region
  - Discrimination - can you tell signal from background (gamma rays, alphas, neutrons, etc)?

Electronic recoils (gammas) vs. nuclear recoils (WIMPs)

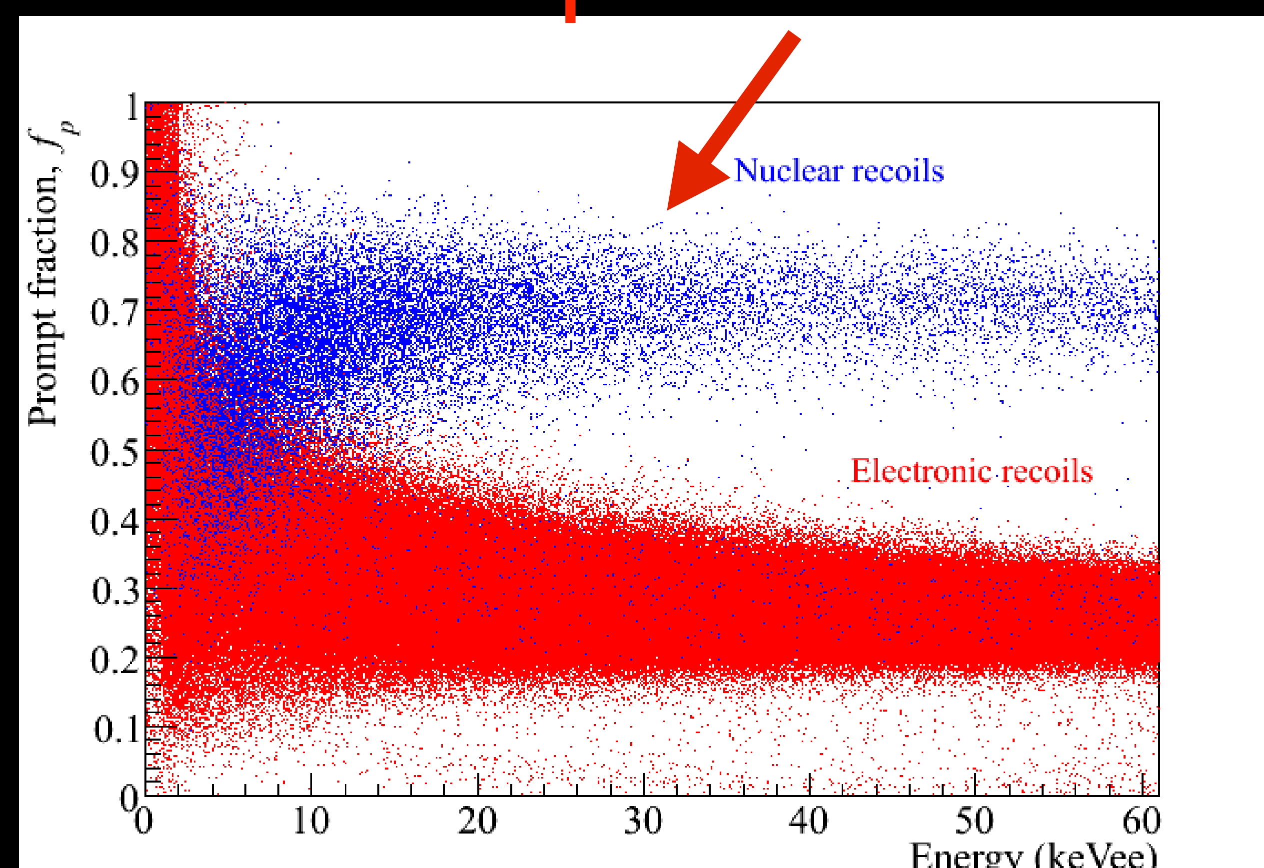
CDMS - Charge to heat



Xenon TPCs - Charge to light



Argon - Pulse shape discrimination



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  - All experiments have to go underground to get away from cosmic rays
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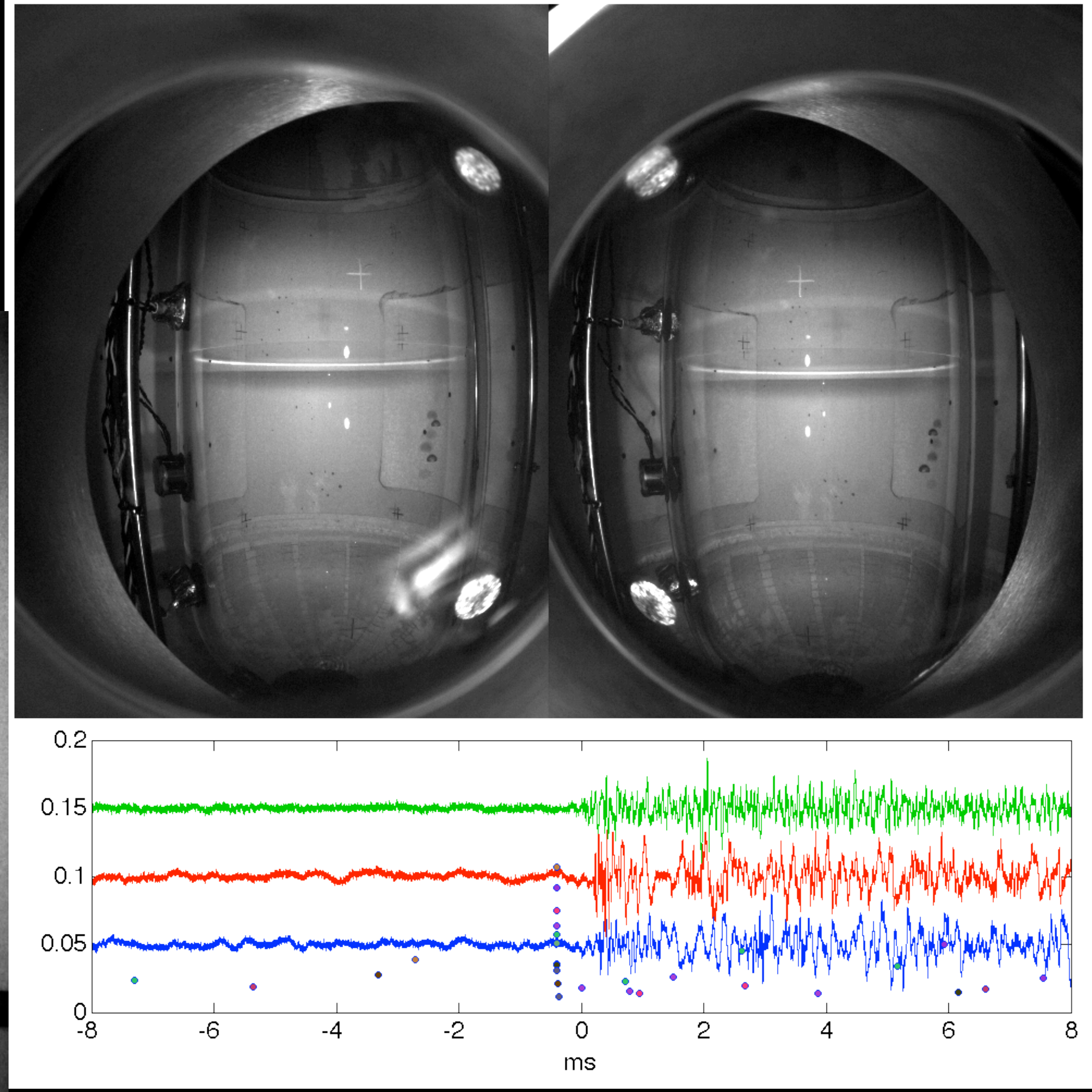
Bubble Chambers!

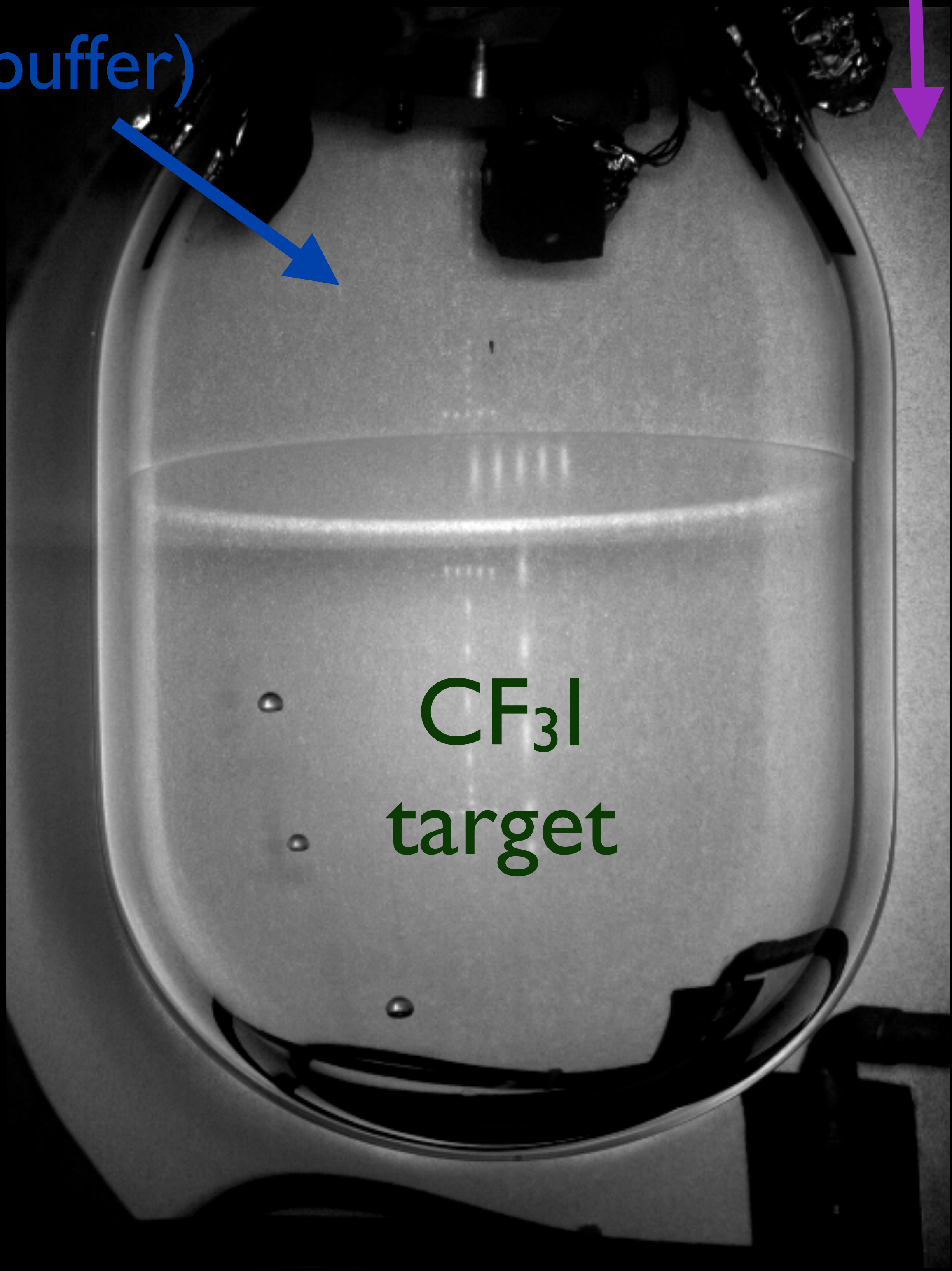
Chicagoland Observatory for Underground Particle Physics (COUPP)

[Some debate over the pronunciation (should the Ps be silent?)]



COUPP bubble chamber

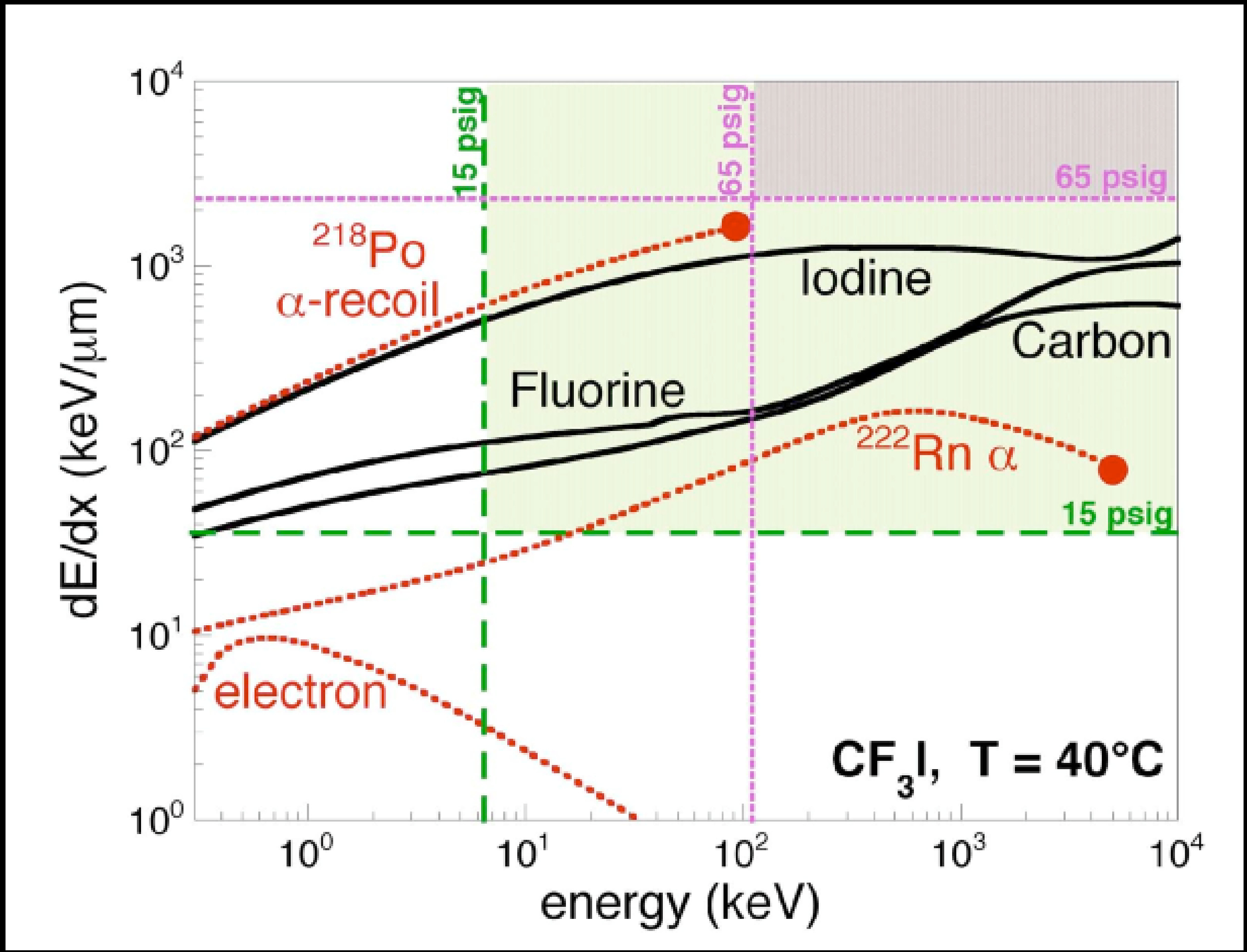
- Pressure expansion creates superheated fluid, CF_3I
  - F for spin-dependent
  - I for spin-independent
  - Alternatives - e.g. C_3F_8
- Particle interactions nucleate bubbles
- Cameras see bubbles
- Recompress chamber to reset



Why bubble chambers?

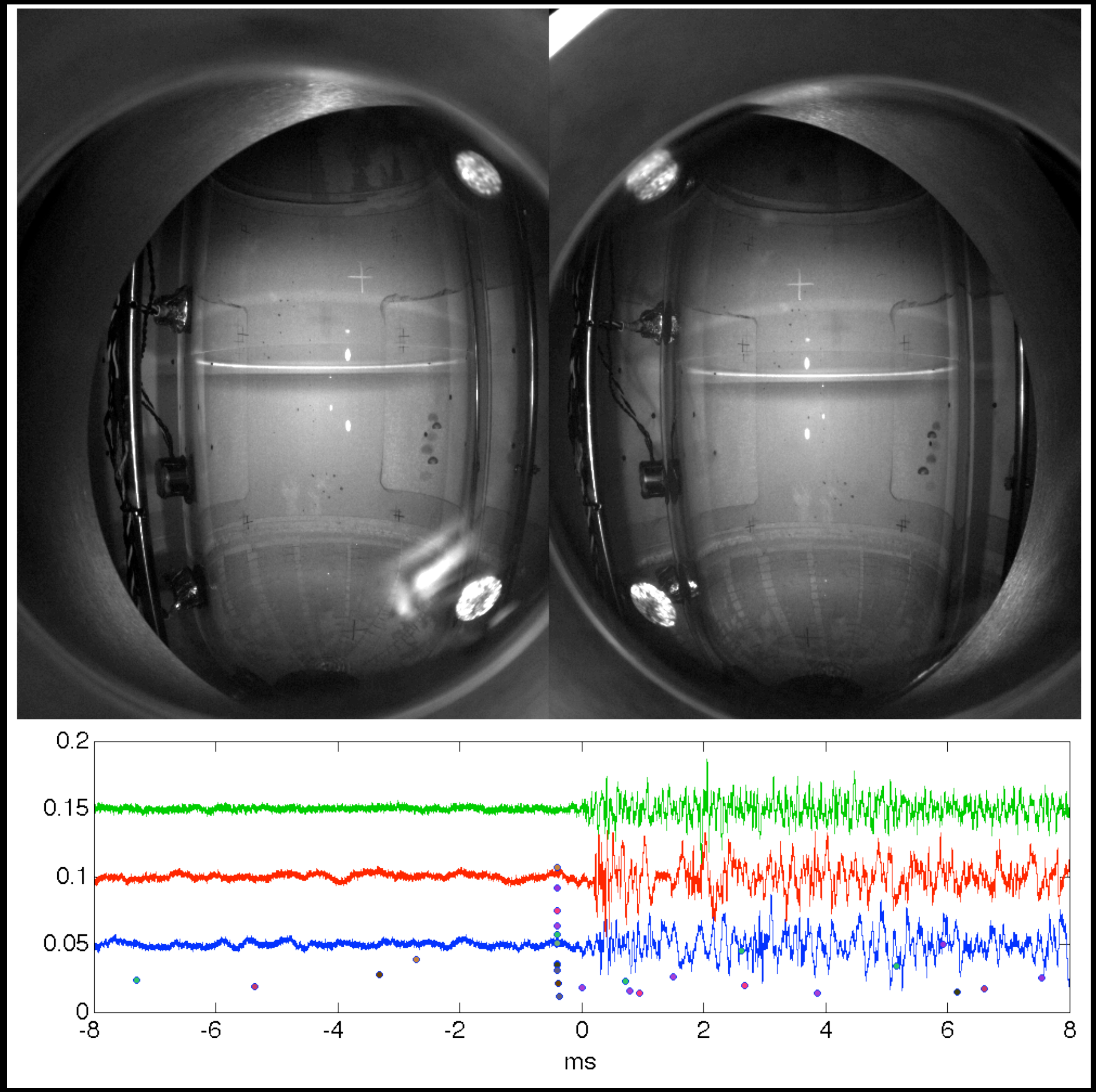
- To form a bubble requires two things
  - Enough energy
  - Enough energy density - length scale must be comparable to the critical bubble size
- By choosing superheat parameters appropriately (temperature and pressure), bubble chambers are blind to electronic recoils

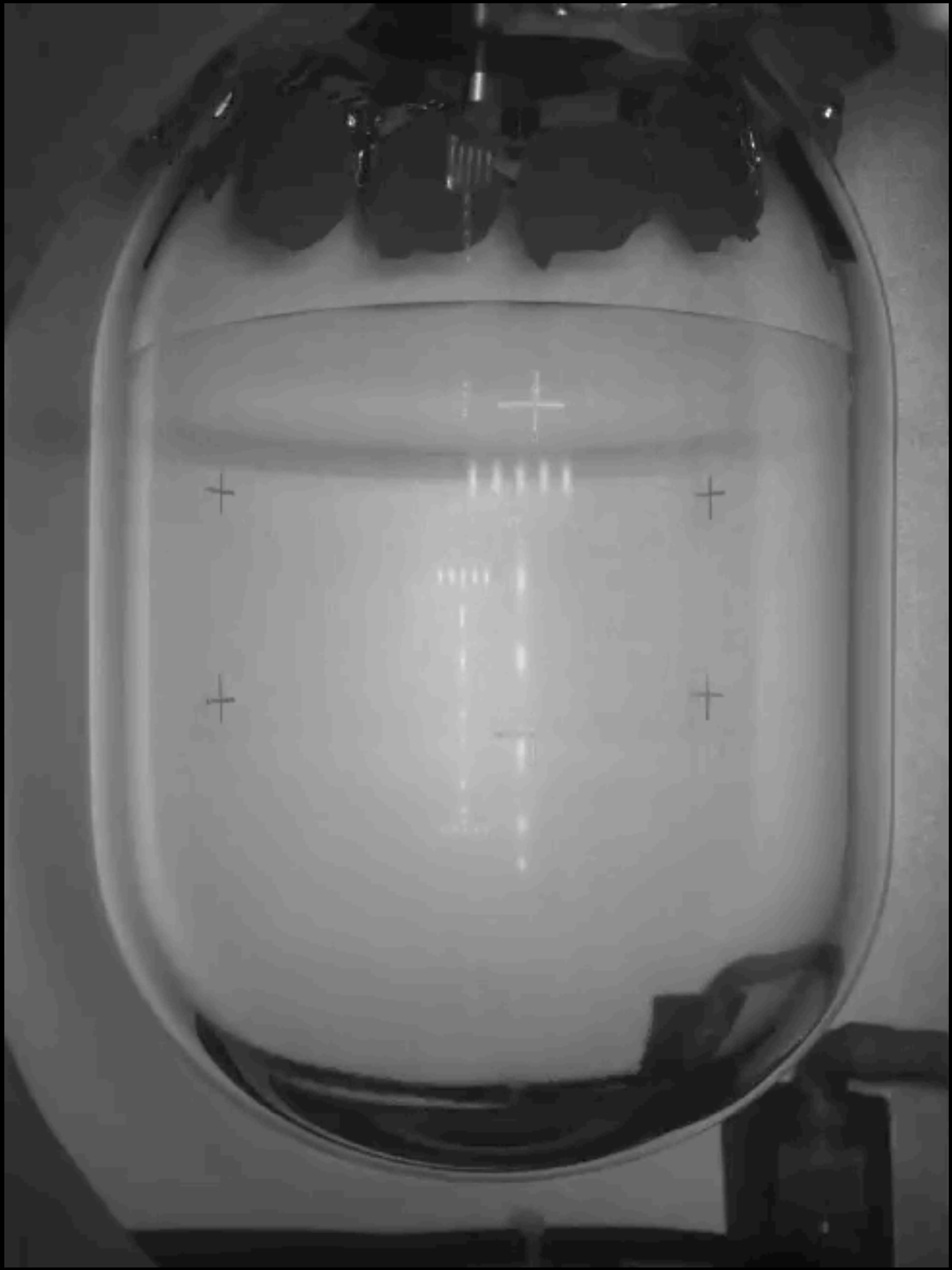
Why bubble chambers?



Why bubble chambers

- Easy to identify multiple scattering events → Neutron backgrounds
- Easy DAQ and analysis chain
  - Cameras
  - Piezos
- No PMTs, no cryogenics



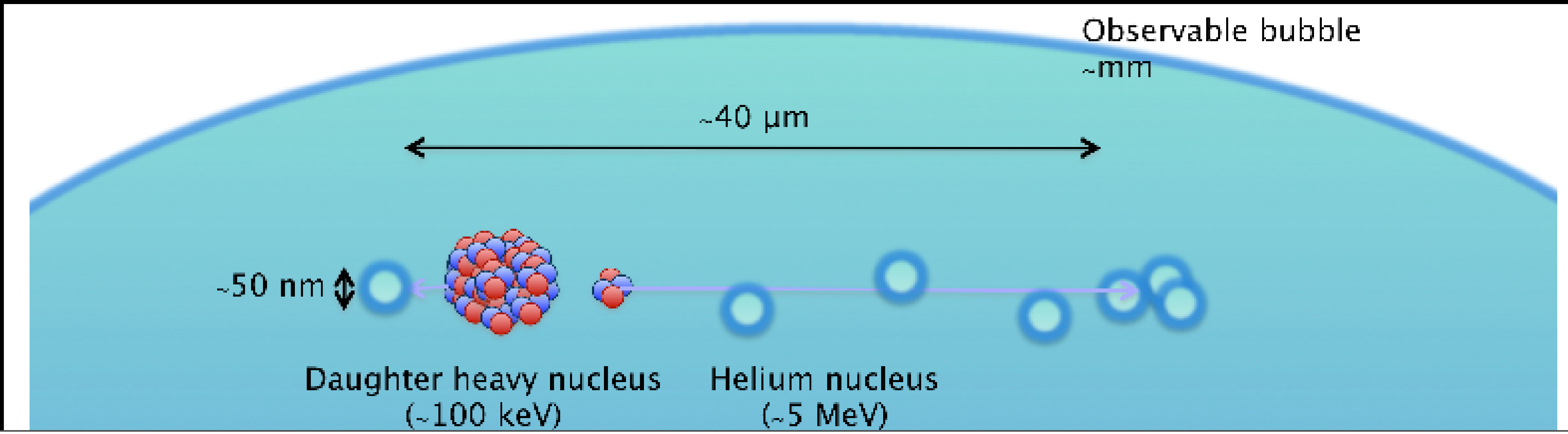


Why not bubble chambers?

- Threshold detectors - no energy resolution
  - Harder to distinguish some backgrounds, less information about any potential signal
    - Alphas (several MeV) were a big concern
  - Energy threshold calibrations are hard and important
- Bubble chambers are slow - about 30 s of deadtime for every event
  - Overall rate must be low

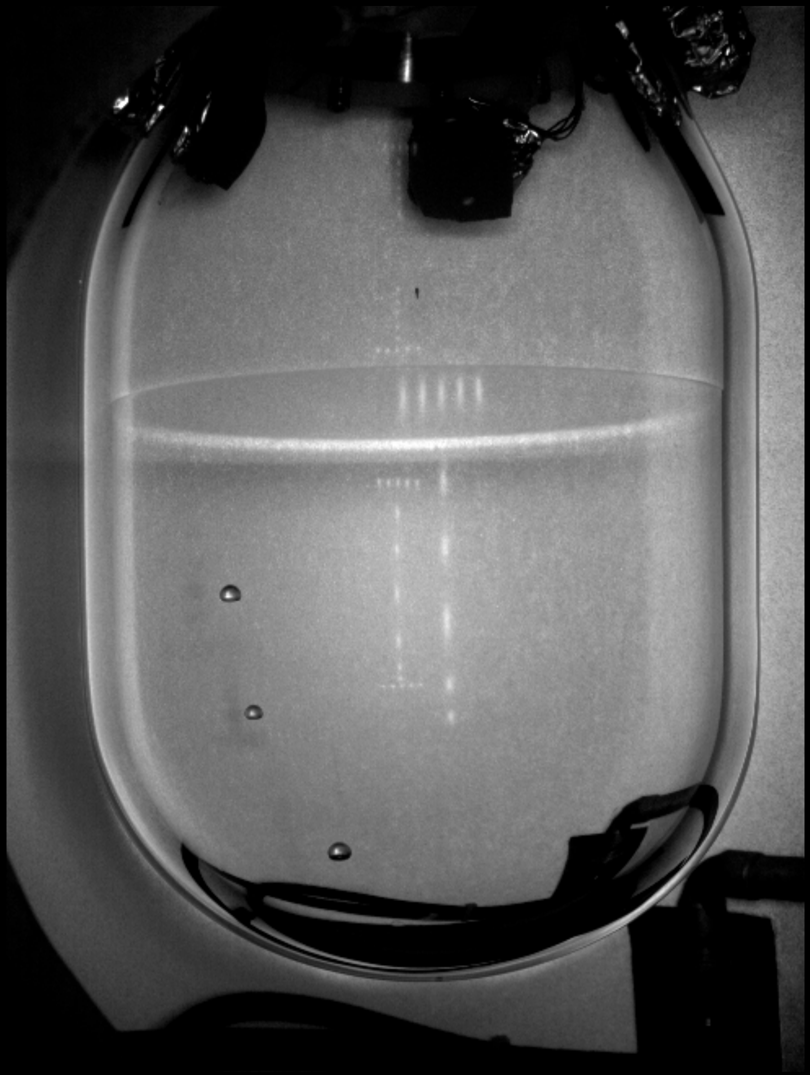
About those alphas

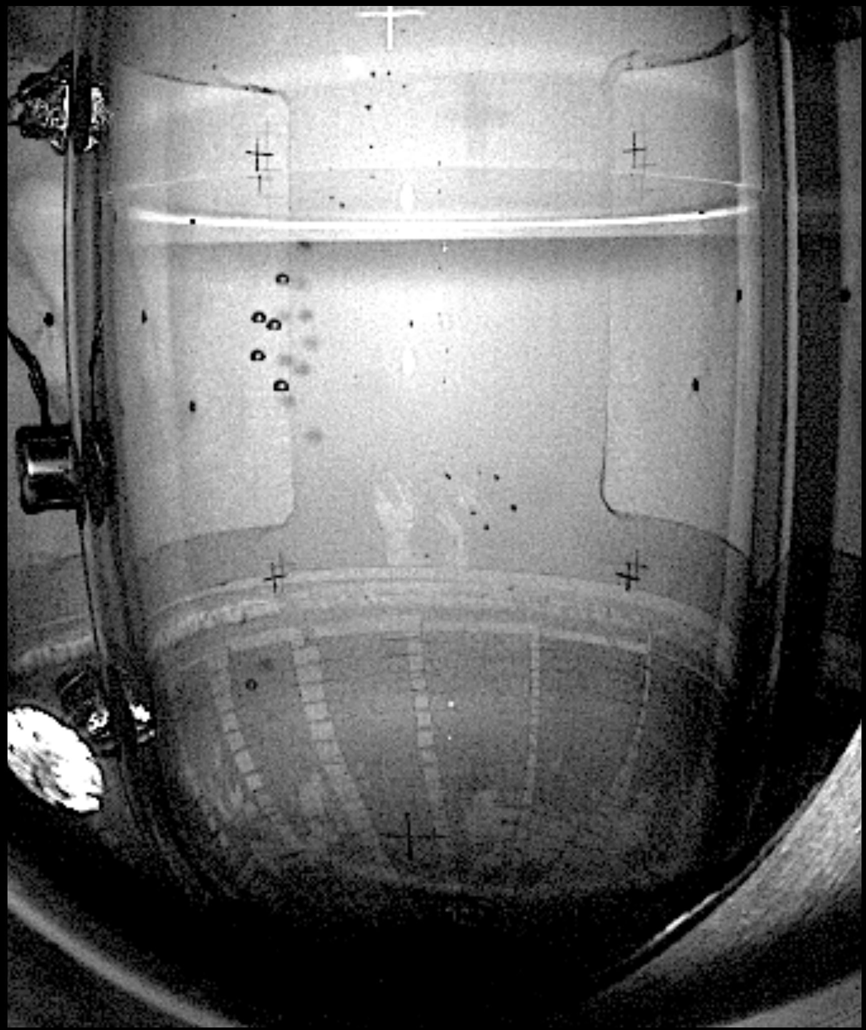
- Discovery of acoustic discrimination against alphas by PICASSO (Aubin et al, New J. Phys 10:103017, 2008)
  - Alphas deposit energy over tens of microns
  - Nuclear recoils deposit theirs in tens of nanometers
- In COUPP bubble chambers, alphas are several times louder



The COUPP program

- COUPP4: A 2-liter chamber operating at SNOLAB since 2010
- COUPP60: Up to 40 liters, commissioning at SNOLAB now
- COUPP500: Ton scale detector, funded by NSF and DOE, at SNOLAB in 2015?

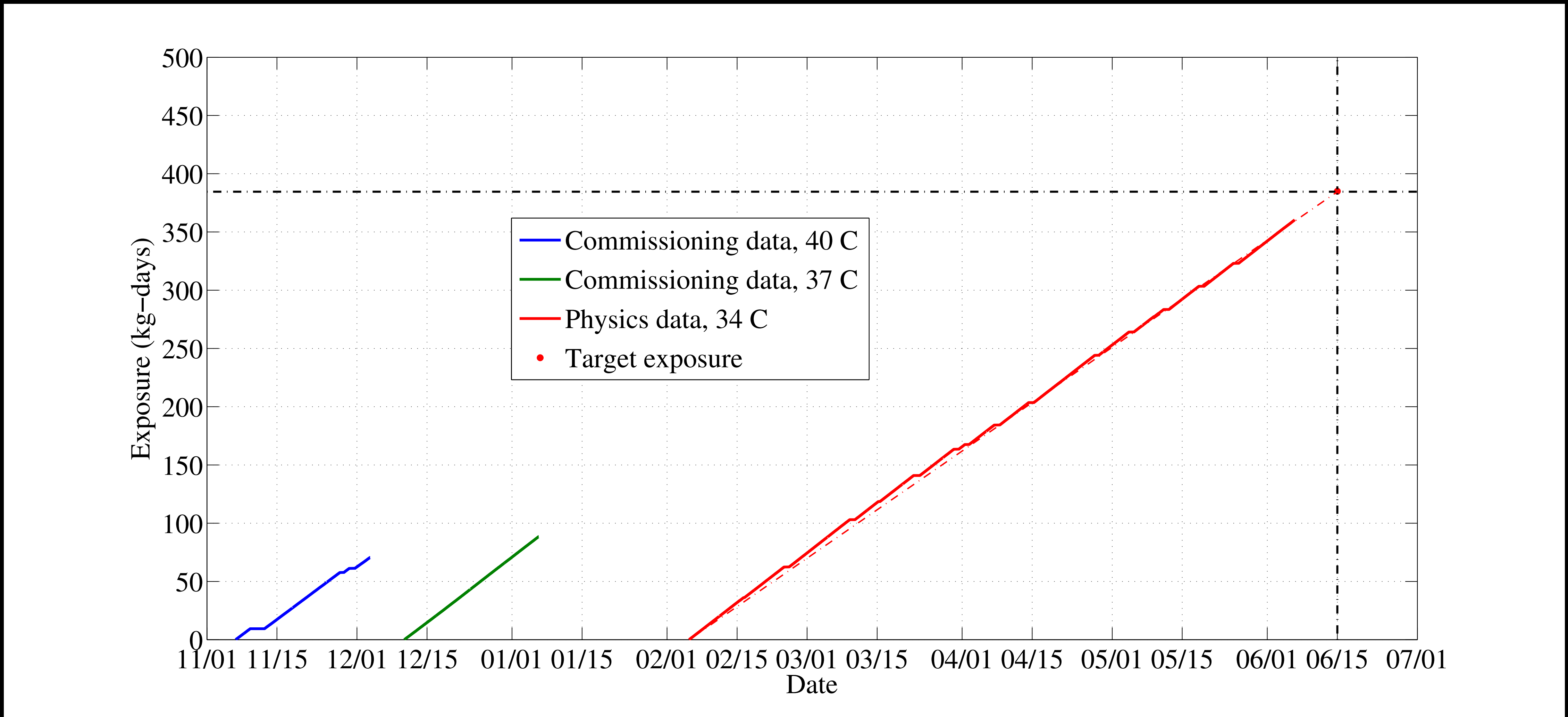




COUPP-4

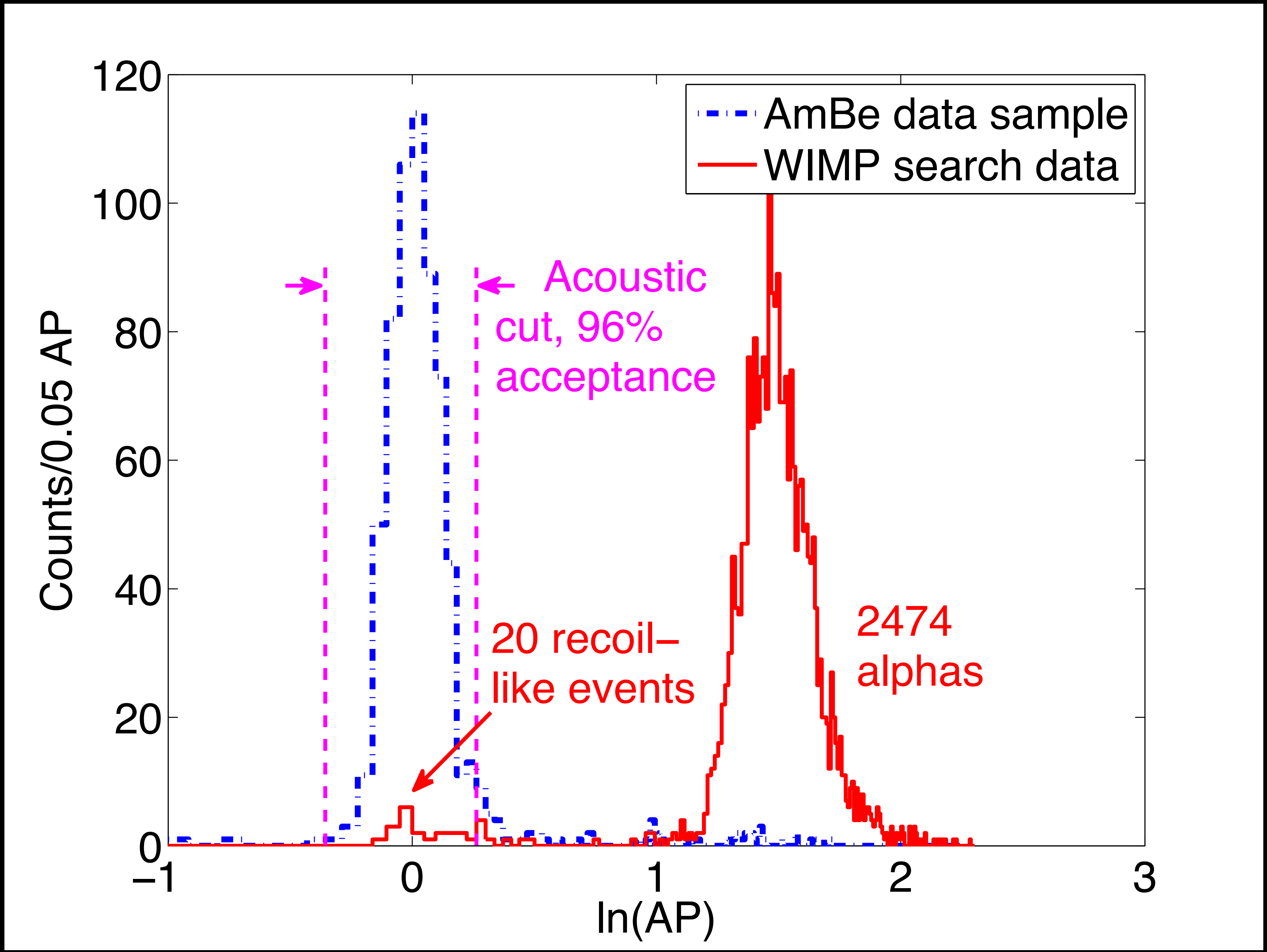
COUPP4: First run 2010-2011

- 17.4 live days at 8 keV threshold
- 21.9 live days at 11 keV threshold
- 97.3 live days at 16 keV threshold
- 79% acceptance for nuclear recoils after all cuts (including fiducial)

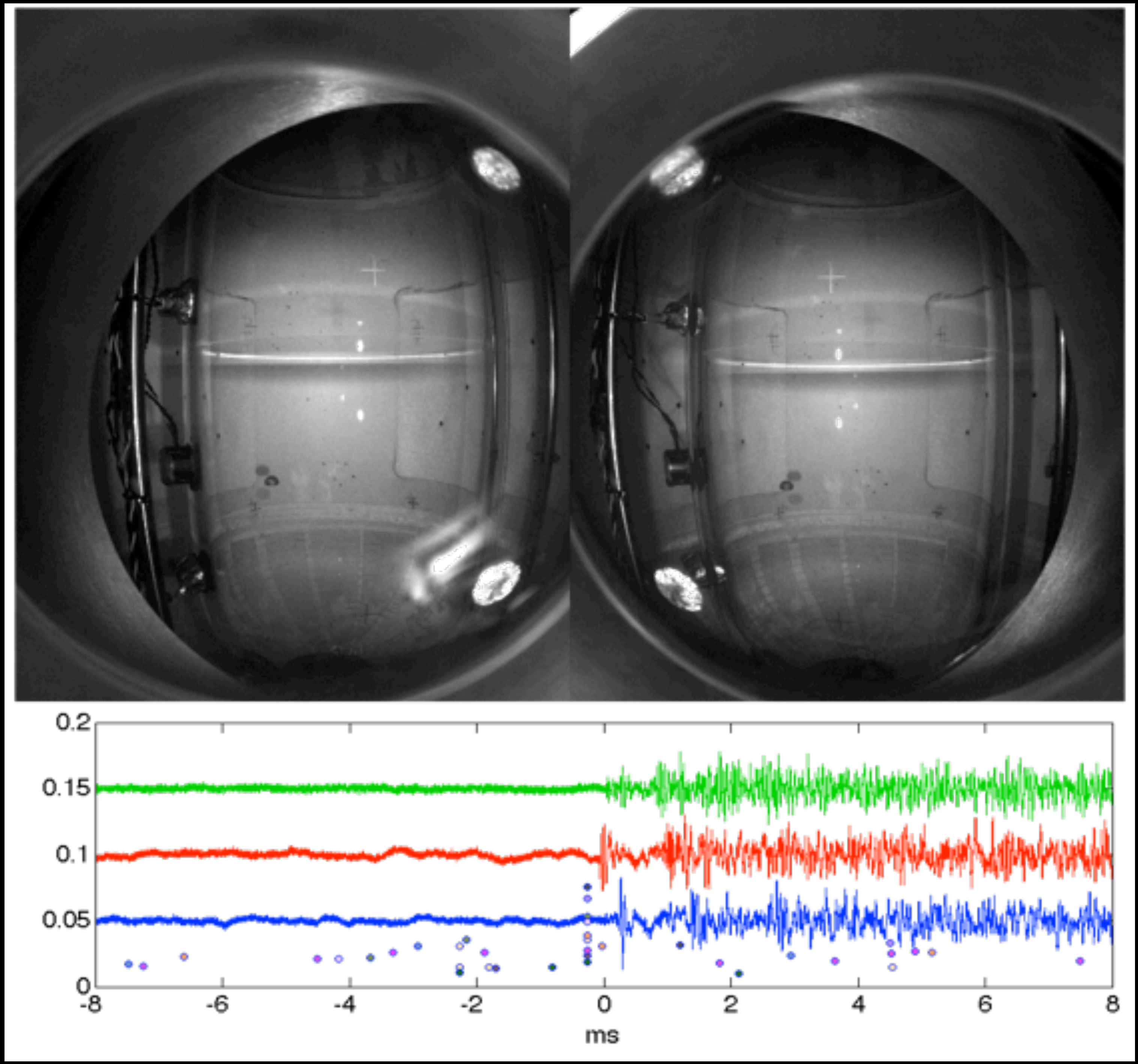


COUPP4: Acoustic discrimination

- Better than 99.3% rejection against alphas at 16 keV threshold
  - Limited by statistics, and backgrounds



This is what dark matter would sound like



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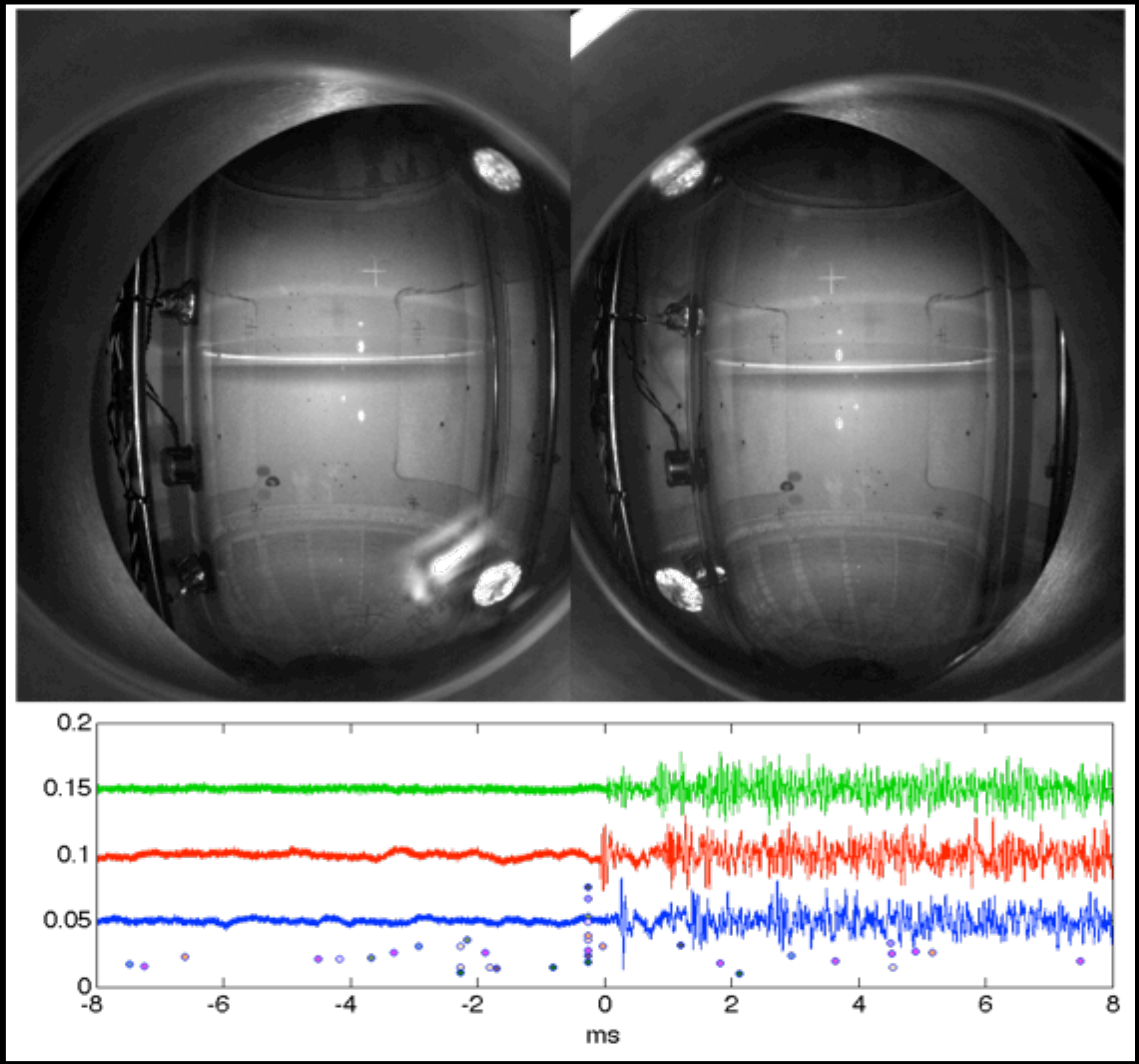
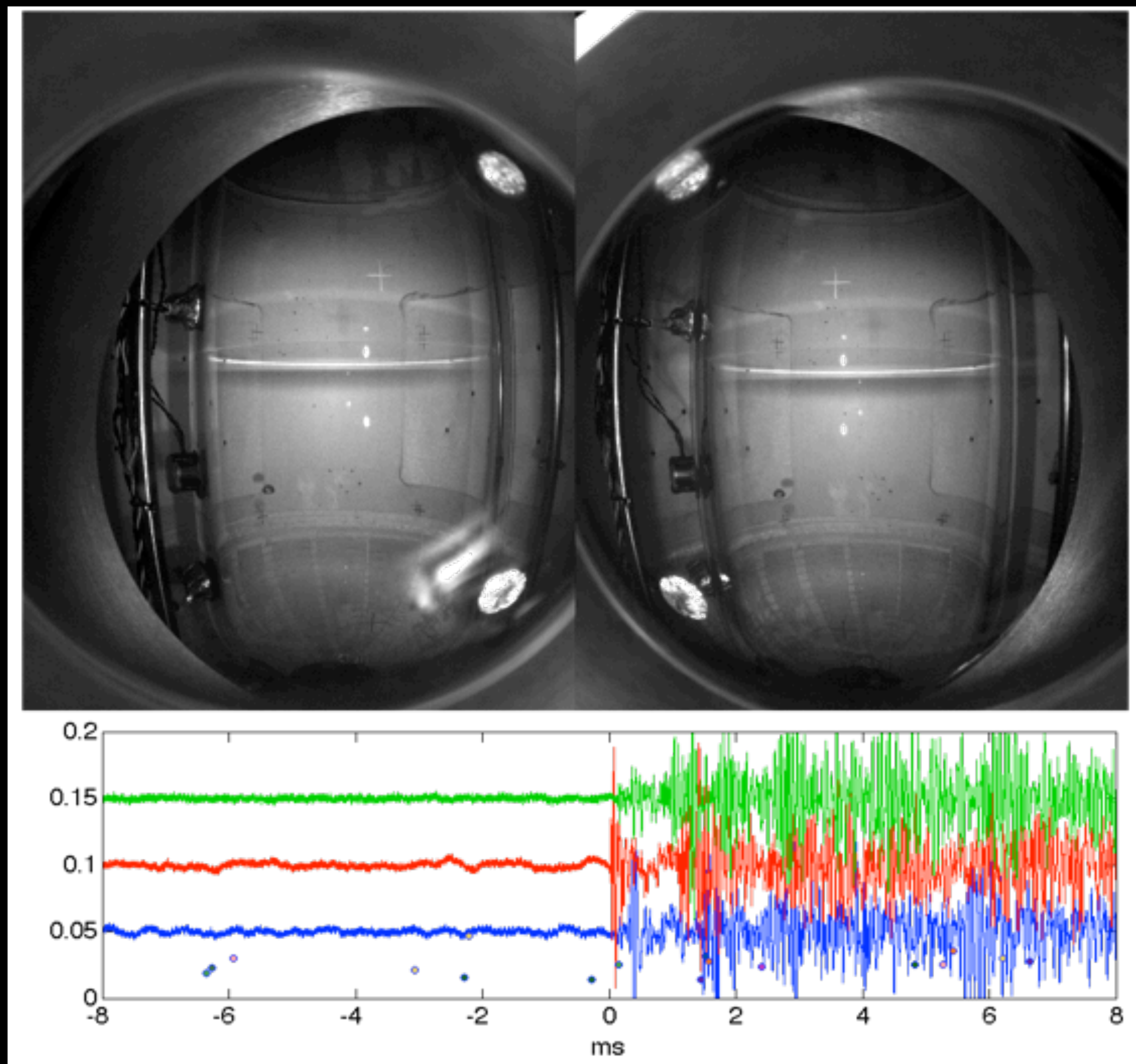


This is what an alpha sounds like



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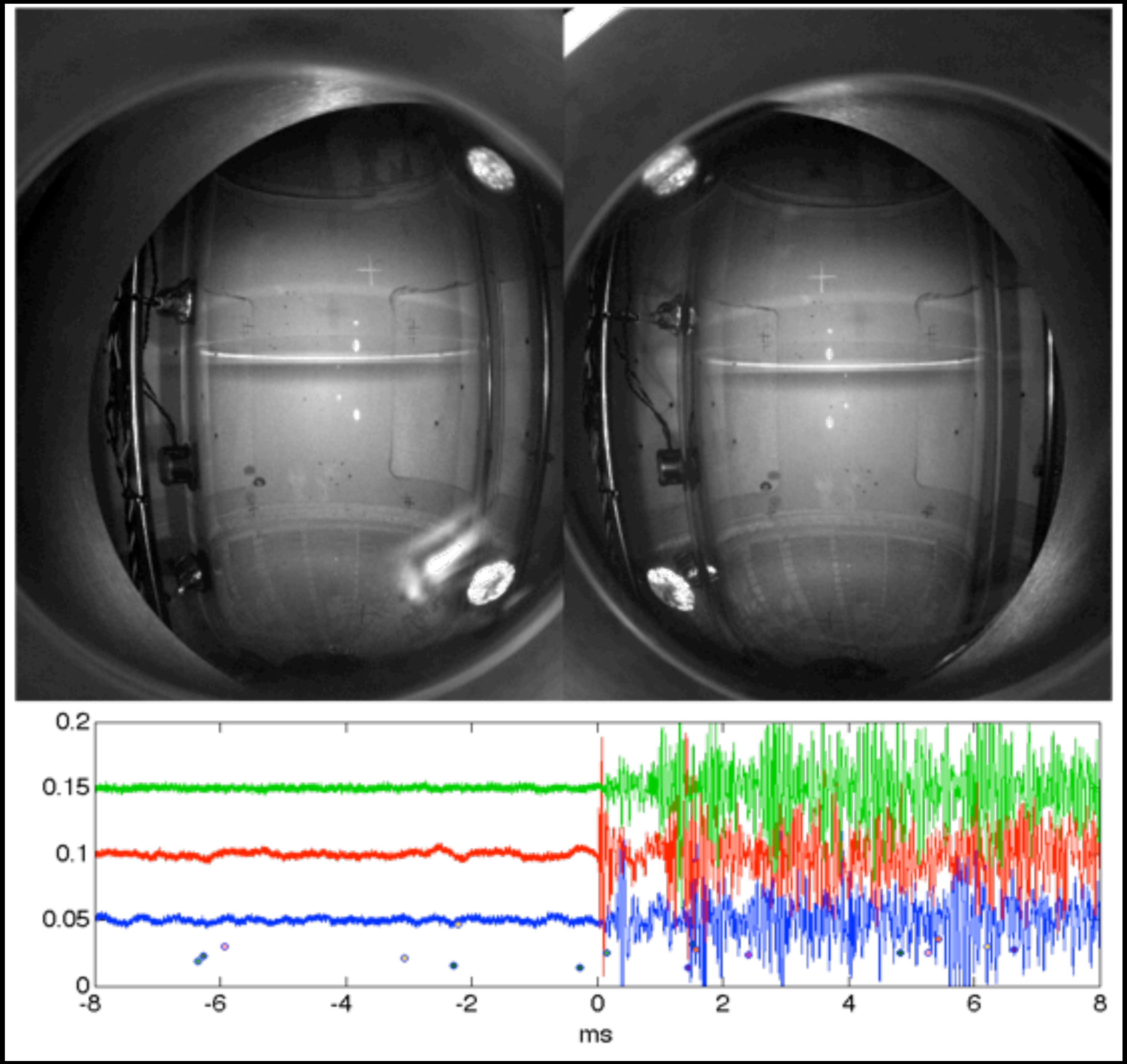
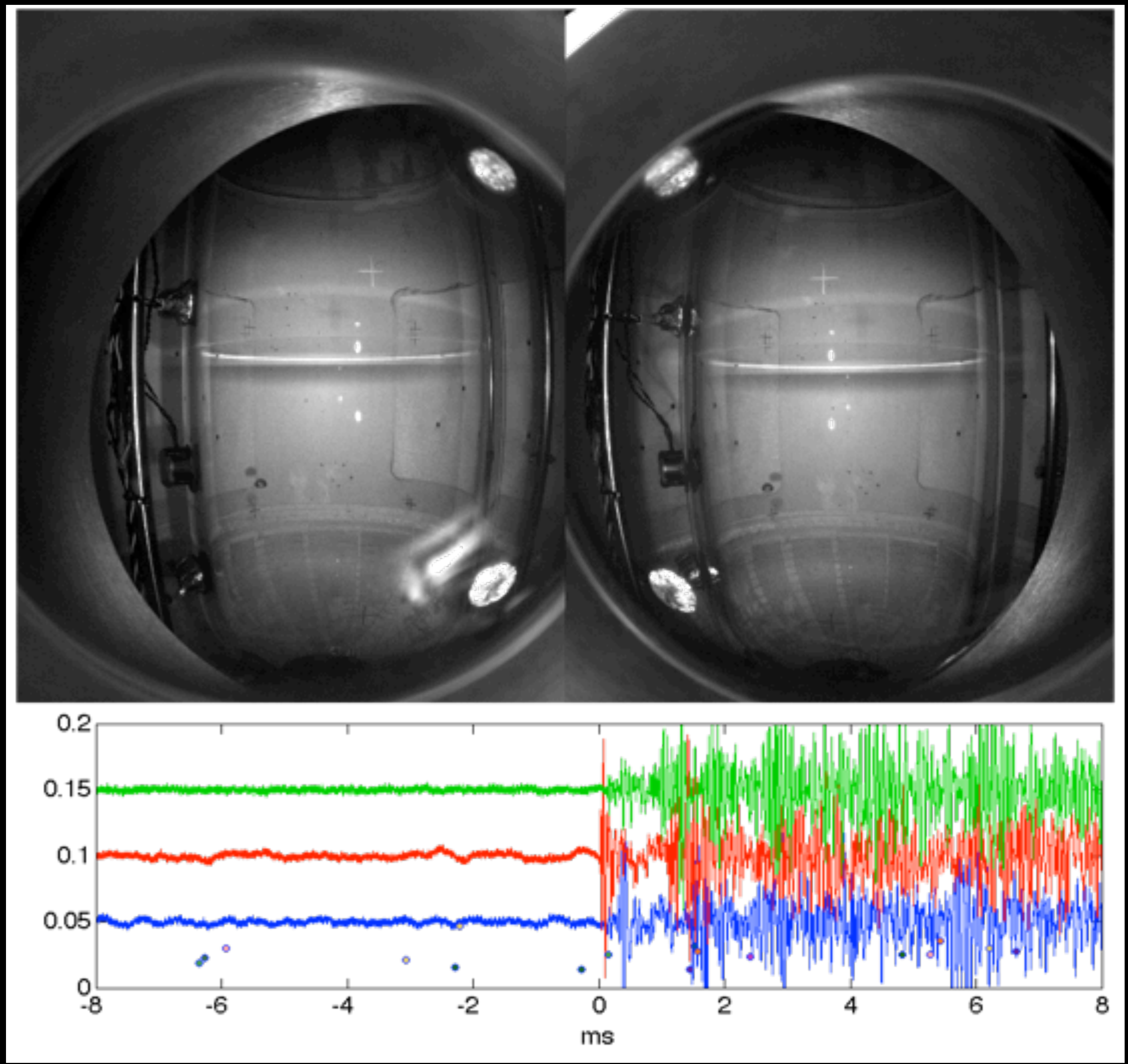


Both together, just to hear the difference



COUPP4: Results and sensitivity

- 20 WIMP candidates (8 at 8 keV, 6 at 11 keV, 8 at 16 keV)
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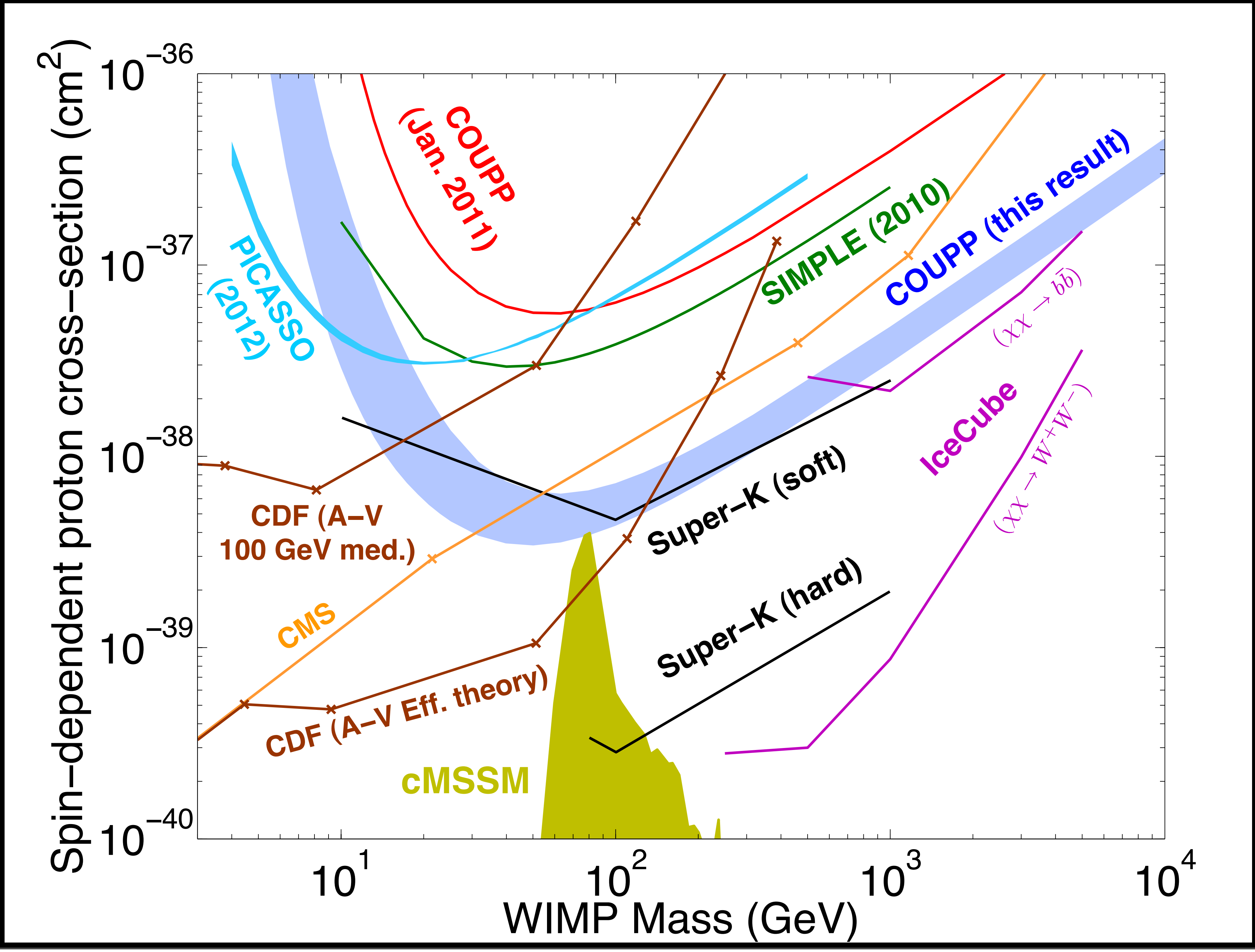
COUPP4: Results and sensitivity

- 20 WIMP candidates (8 at 8 keV, 6 at 11 keV, 8 at 16 keV)
    - 3 multiple bubble events imply neutrons
    - U, Th in the piezo-acoustic sensors and the viewports
- Remaining excess of singles at low threshold
    - Time clustering
    - Correlated with activity at water-CF_3I interface

COUPP4: Results and sensitivity

- Given uncertainties on backgrounds, no background subtraction: PRD 86:052001 (2012)



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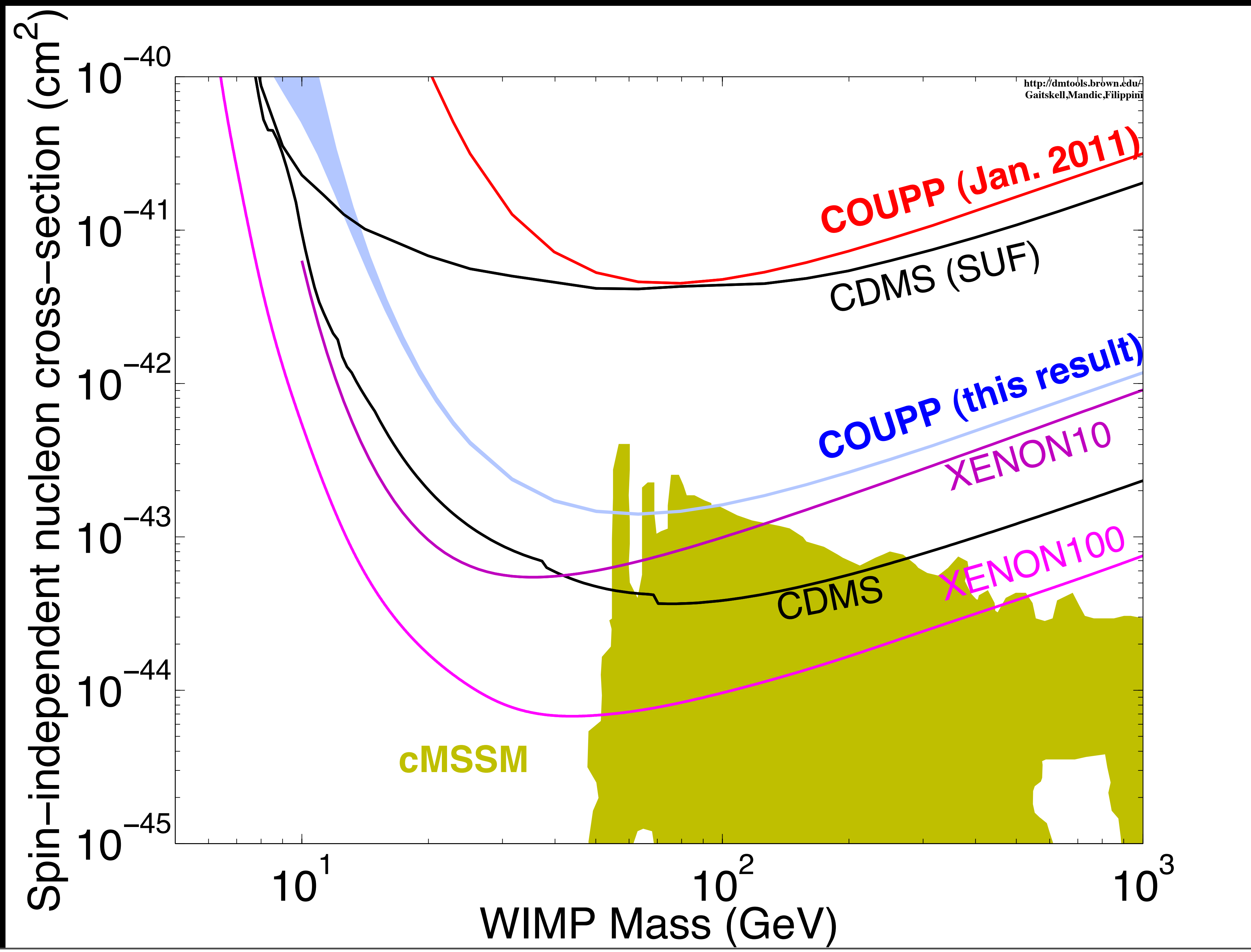
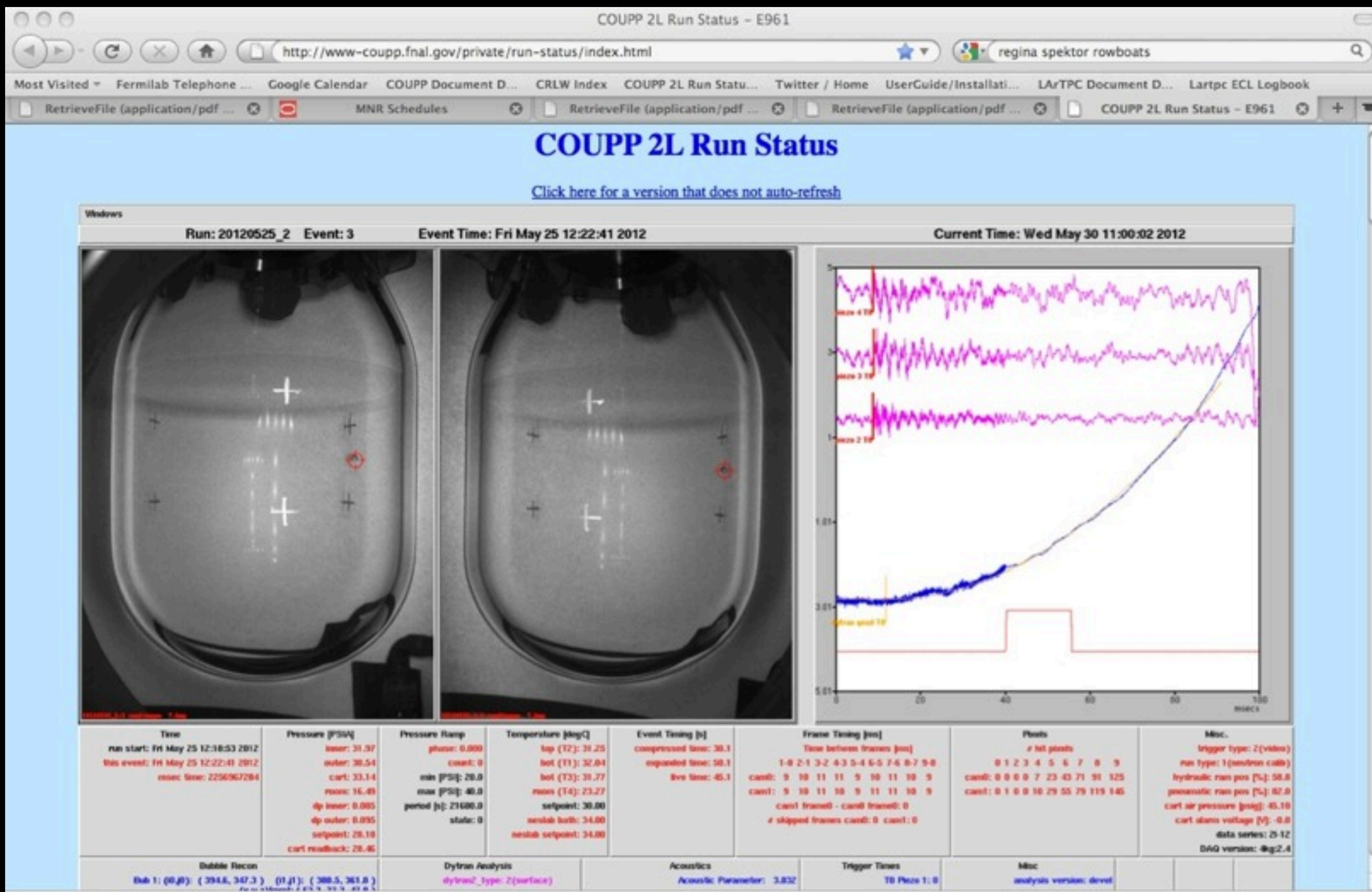


COUPP4: Results and sensitivity

- Removed known neutron sources and improved fluid purification
- Second run ended last November



Detour: Threshold and efficiency

- Threshold determined from Seitz, Phys. of Fluids 1, 2 (1958)

$$p_v - p_l = \frac{2\sigma}{r_c}$$

$$E_{th} = 4\pi r_c^2 \left(\sigma - T \frac{\partial \sigma}{\partial T} \right) + \frac{4}{3}\pi r_c^3 \rho_v h$$

Surface energy

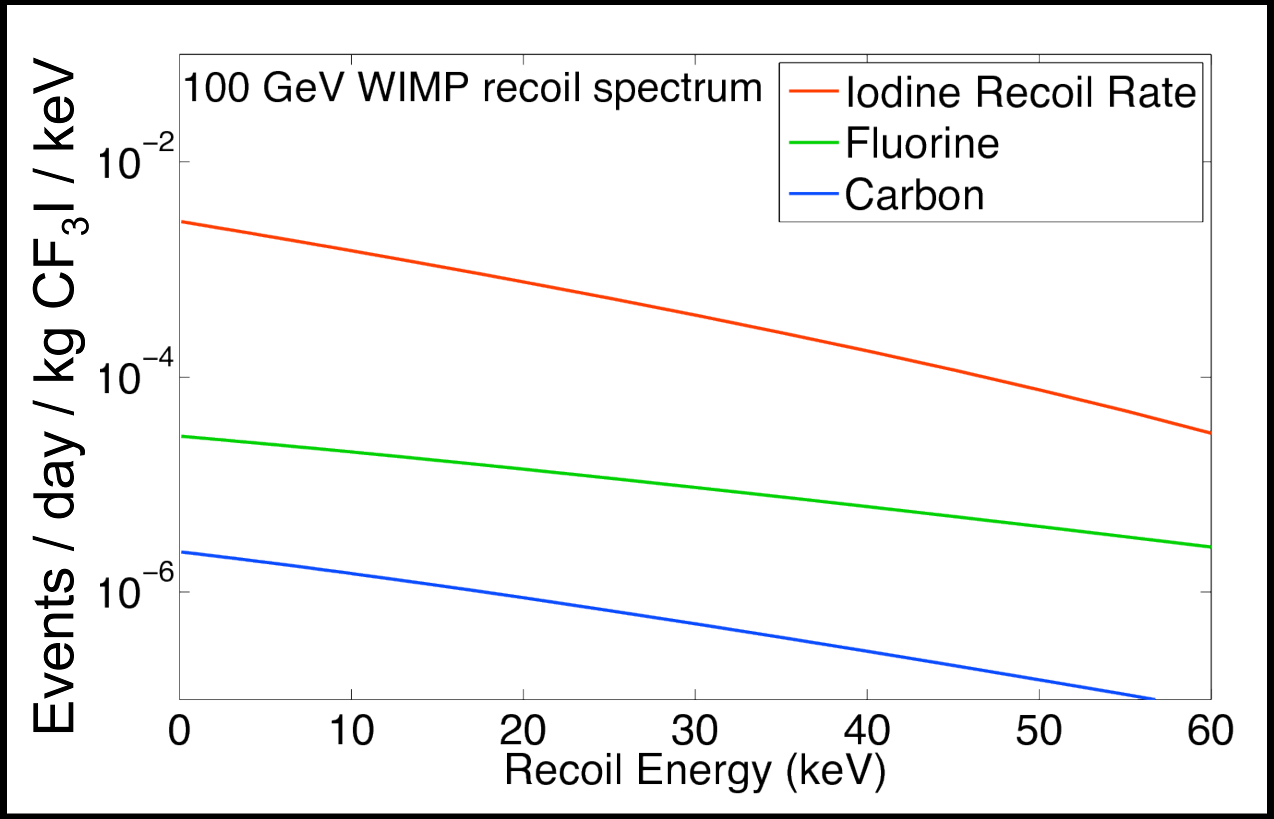
Latent heat

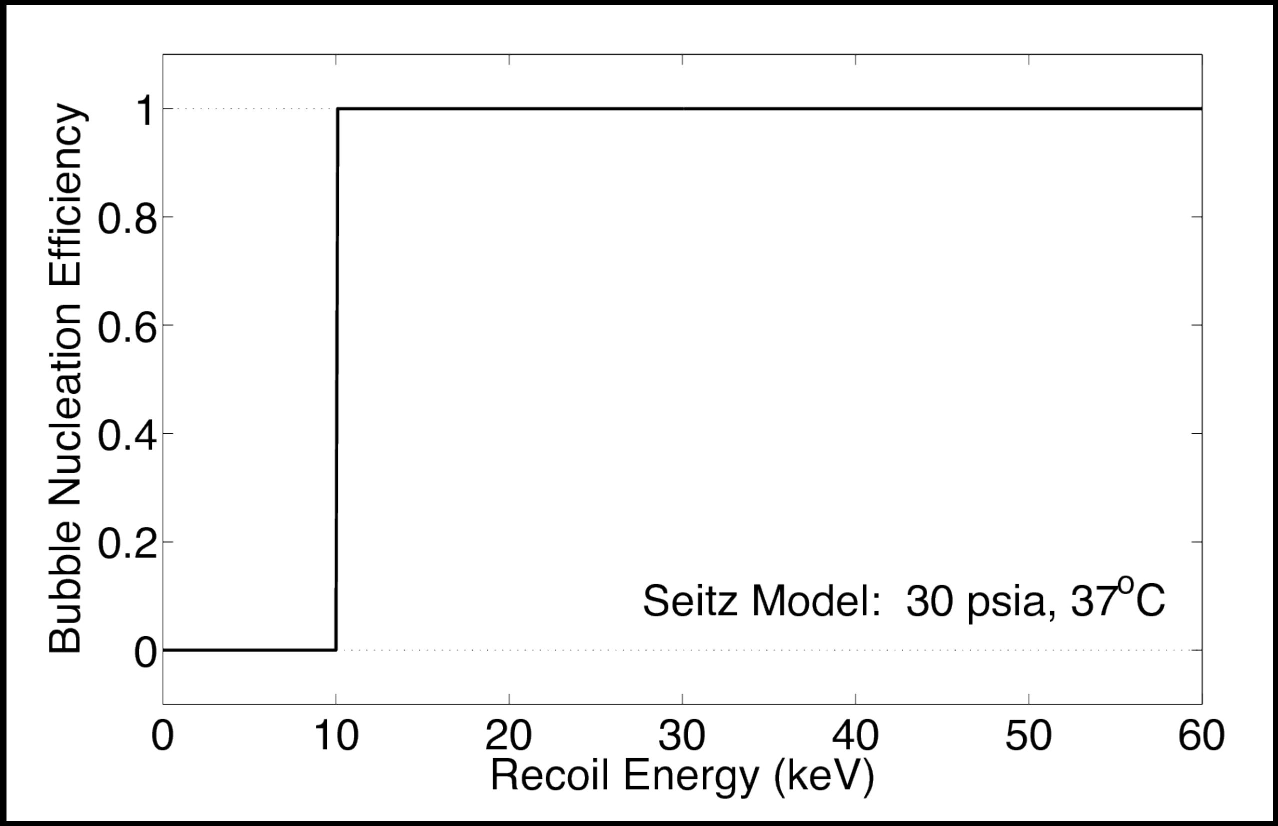
- Energy deposition E_{th} within length R_c will nucleate a bubble (Hot Spike model)

- Theory assumes a step function above threshold

Detour: Threshold and efficiency

$$\text{Rate} = \int \text{WIMP recoil spectrum} \times \text{Bubble nucleation efficiency}$$





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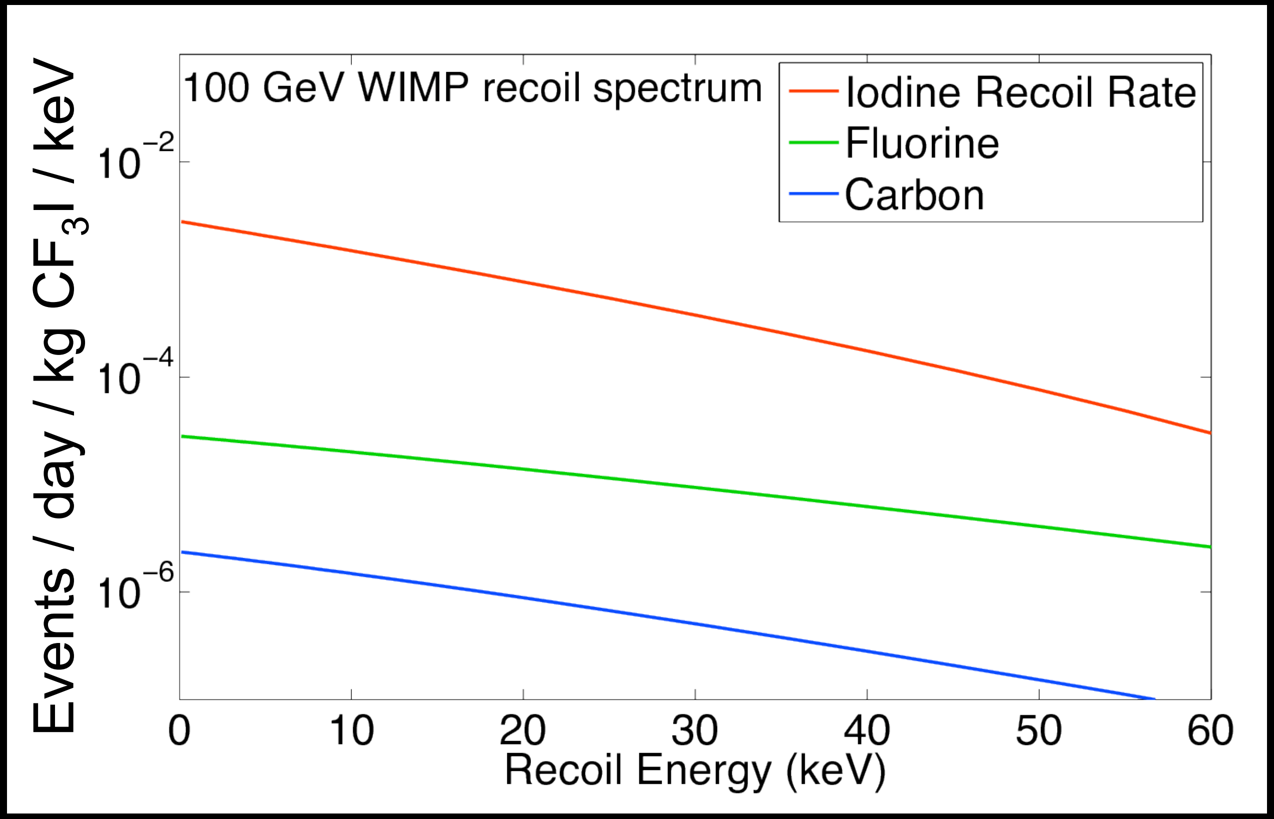

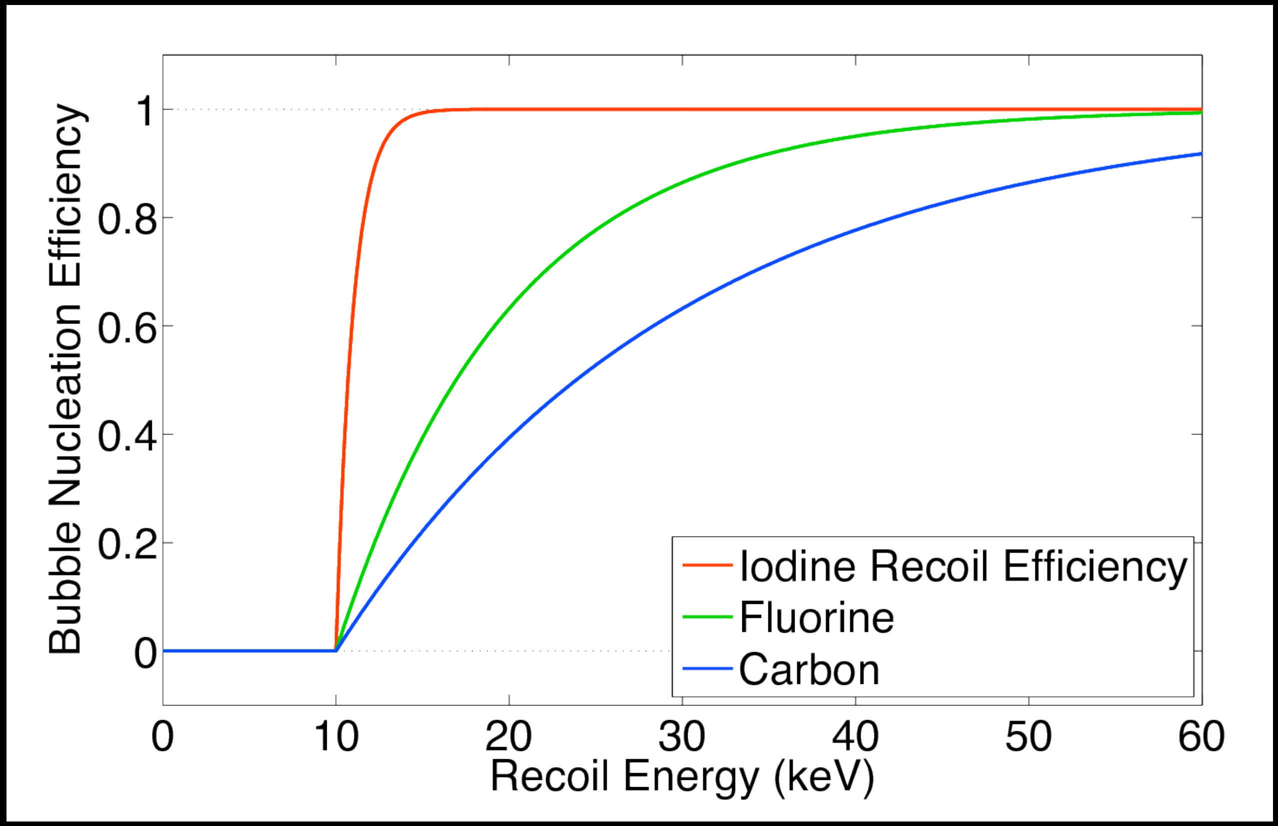

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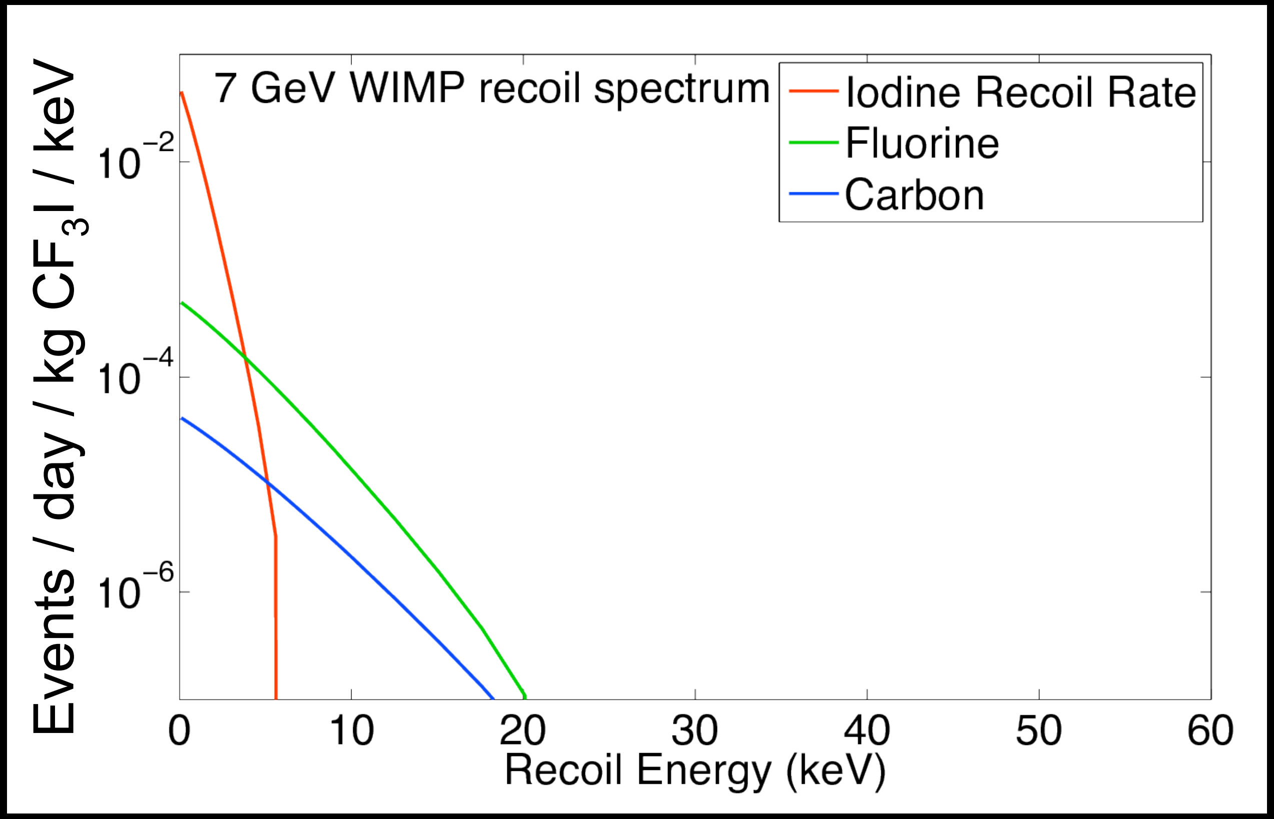
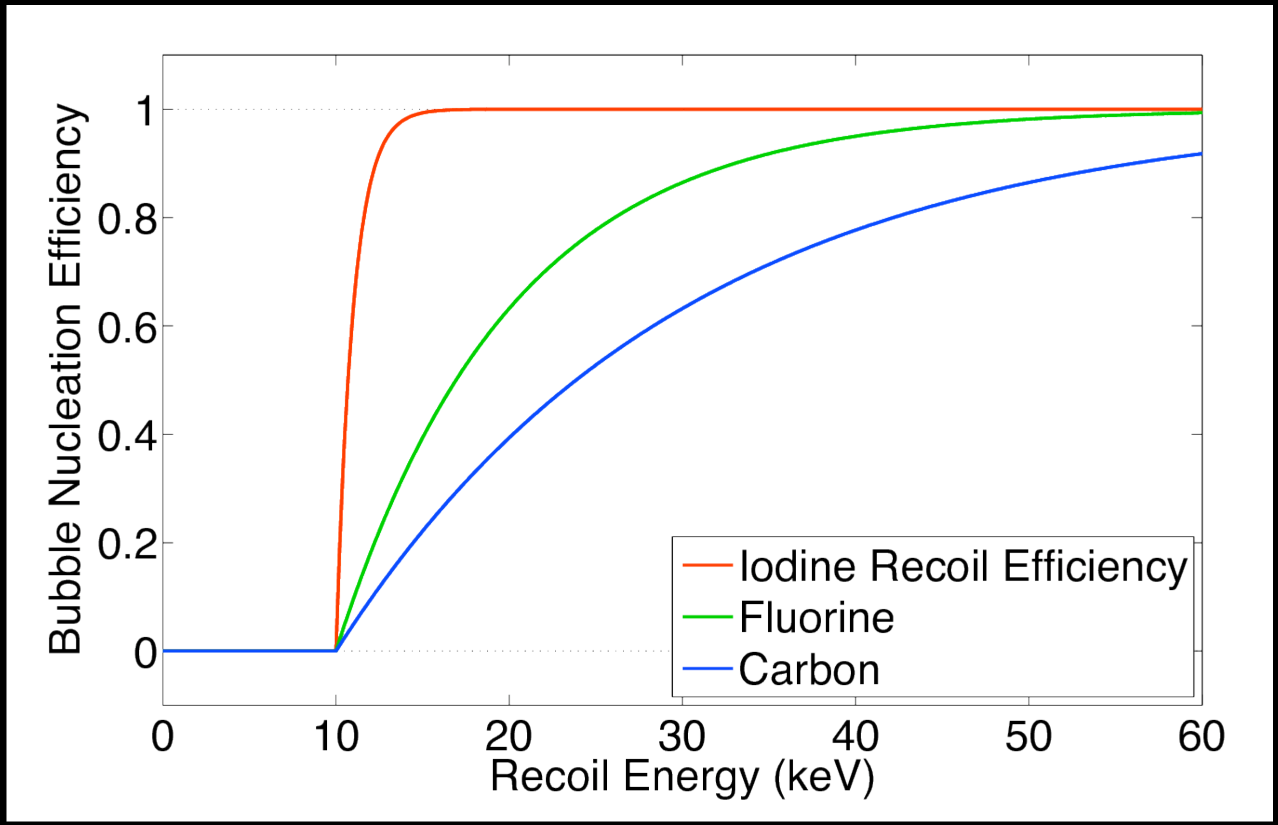




- Effect of threshold shape depends on target, WIMP mass

Detour: Threshold and efficiency

- Threshold determined from Seitz, Phys. of Fluids 1, 2 (1958)

$$p_v - p_l = \frac{2\sigma}{r_c}$$

$$E_{th} = 4\pi r_c^2 \left(\sigma - T\frac{\partial\sigma}{\partial T}\right) + \frac{4}{3}\pi r_c^3 \rho_v h$$

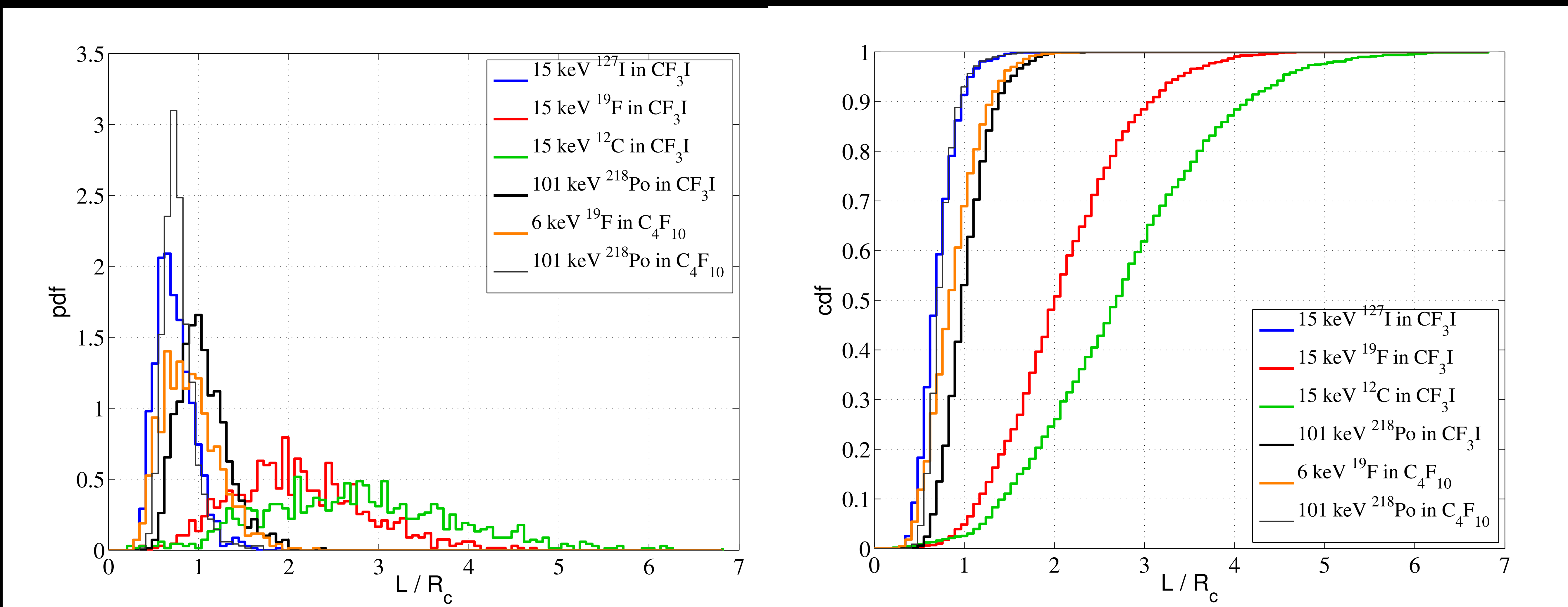
Surface energy

Latent heat

- Energy deposition E_{th} within length r_c will nucleate a bubble (Hot Spike model)
- Theory assumes a step function above threshold
  - Needs calibration

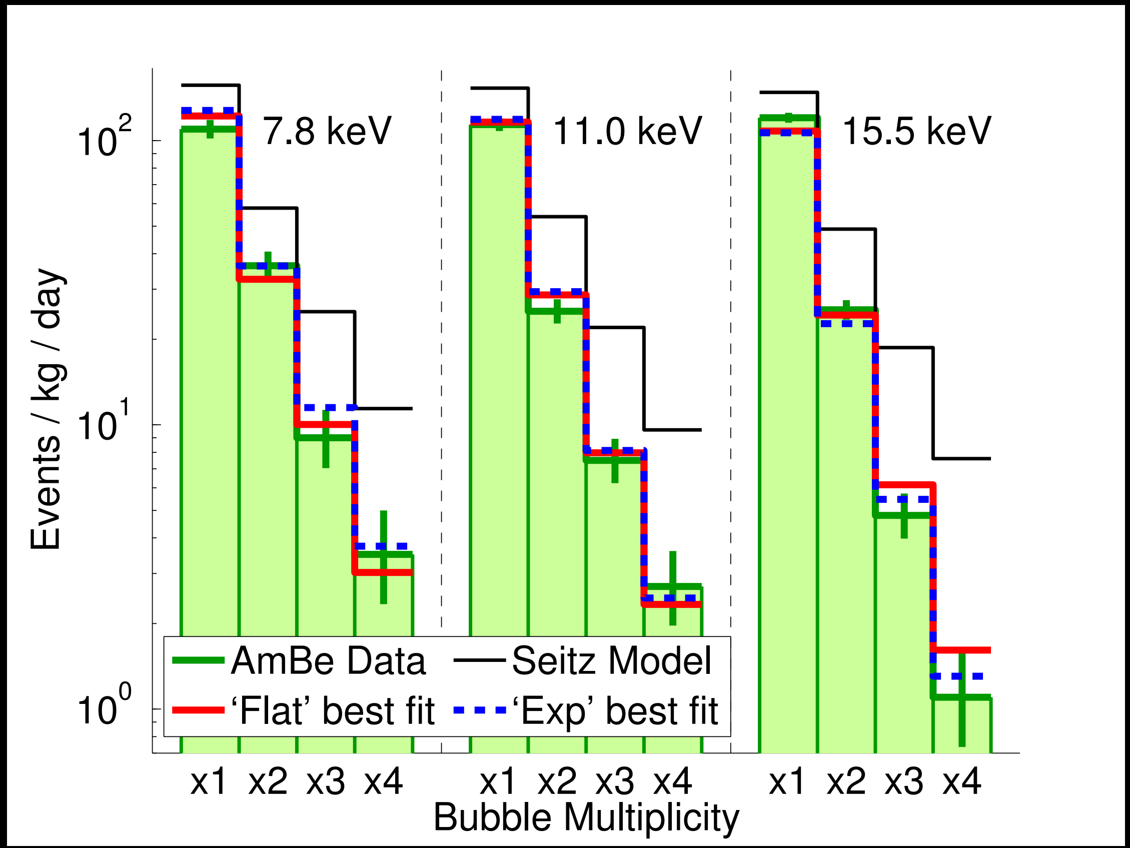
Detour: Threshold and efficiency

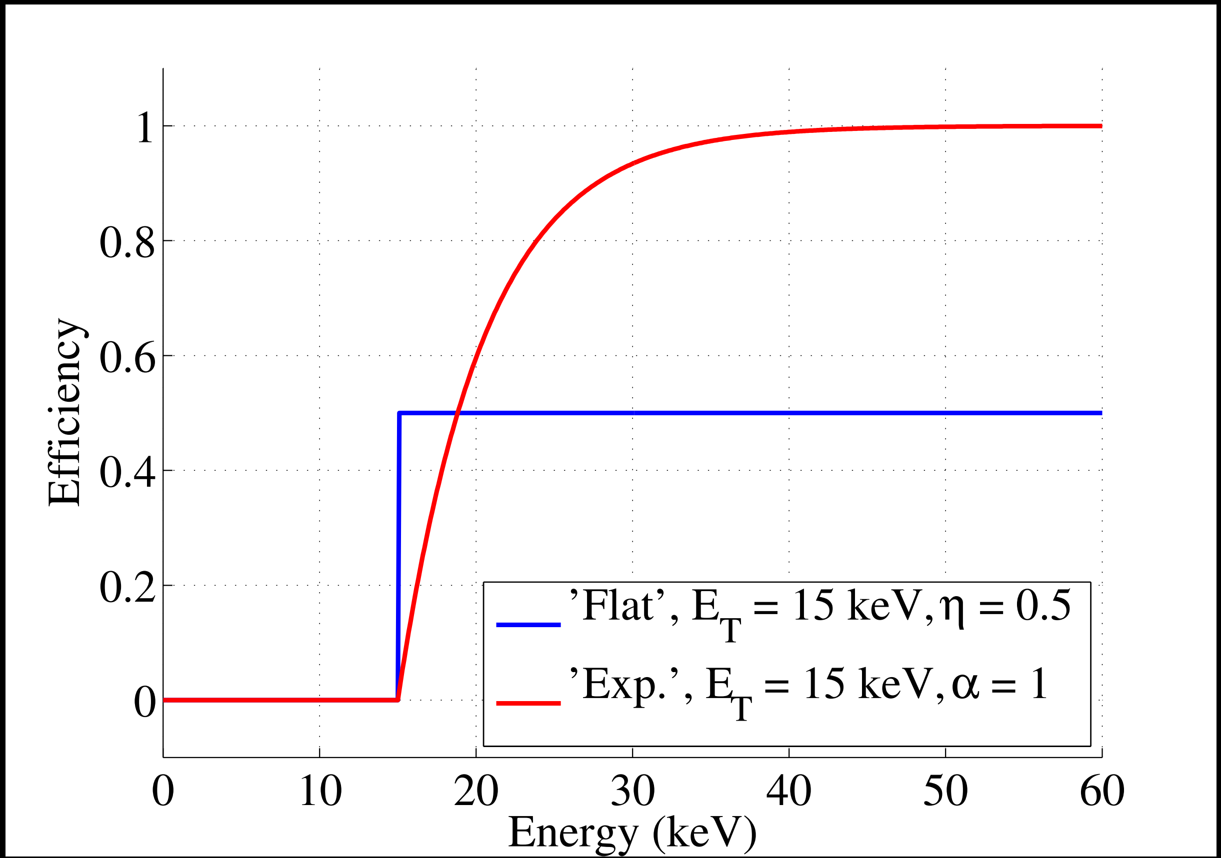
- Complicated by molecule, CF_3I
- Recall that the recoil track length L must be comparable to the bubble radius R_C



Carbon and fluorine

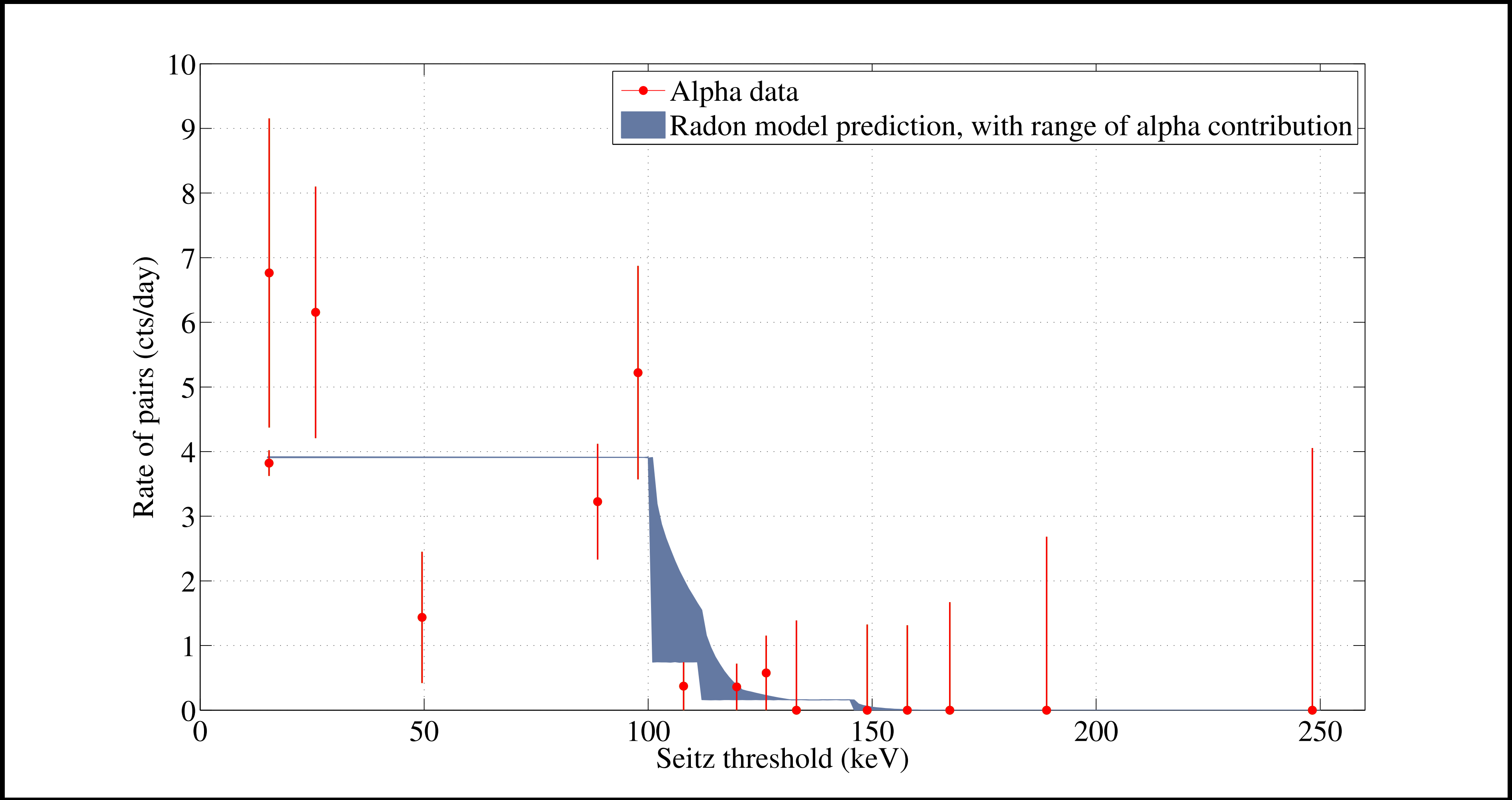
- Use neutron calibration sources at SNOLAB
- Compare MCNP-predicted rates of single, double, triple and quadruple bubble events with observation
- Data show a shortfall of events compared to simulation of the Seitz Model- i.e. the threshold is not a step function





What about iodine?

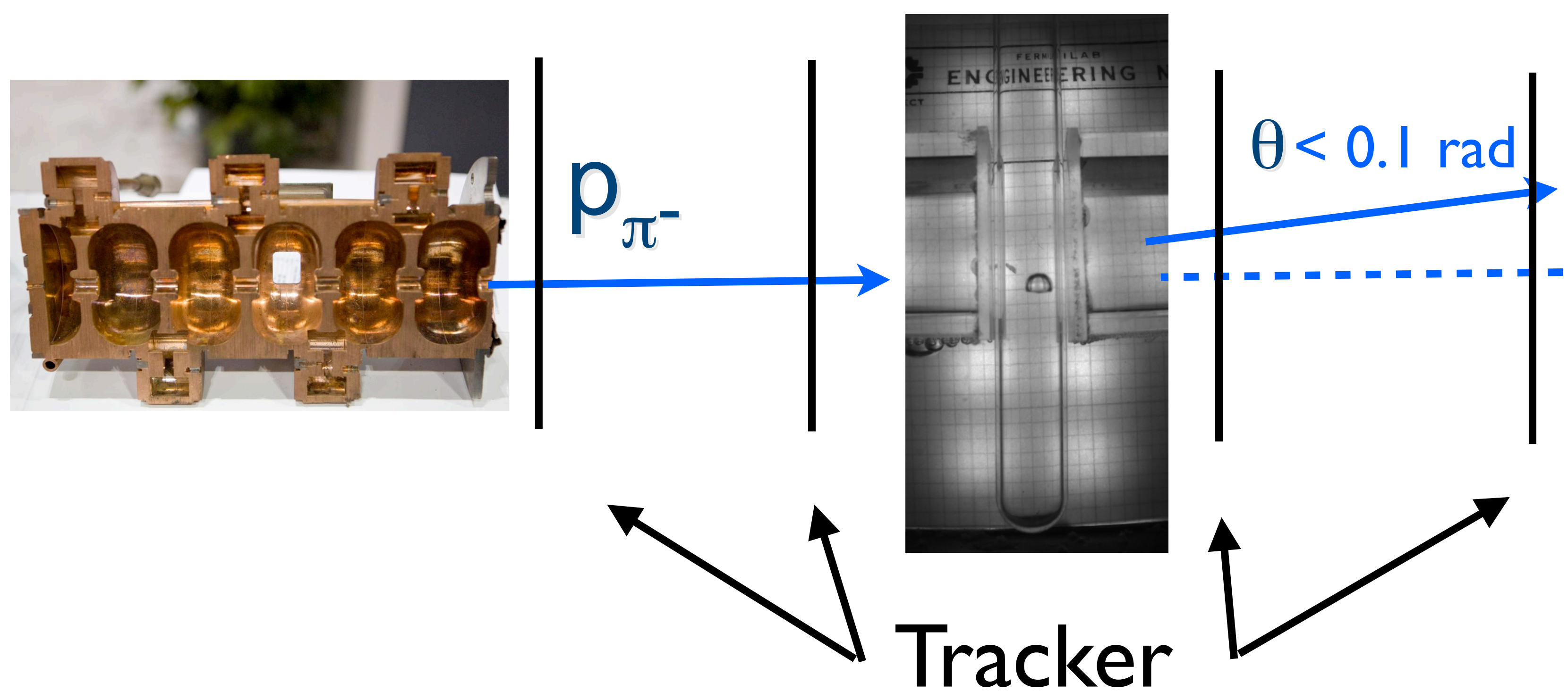
- Main sensitivity to spin independent dark matter from iodine
  - 85% of neutron source interactions are with C and F
- Heavy radon daughter nuclei are a proxy and are step-like



- We really need a direct calibration

COUPP Iodine Recoil Threshold Experiment

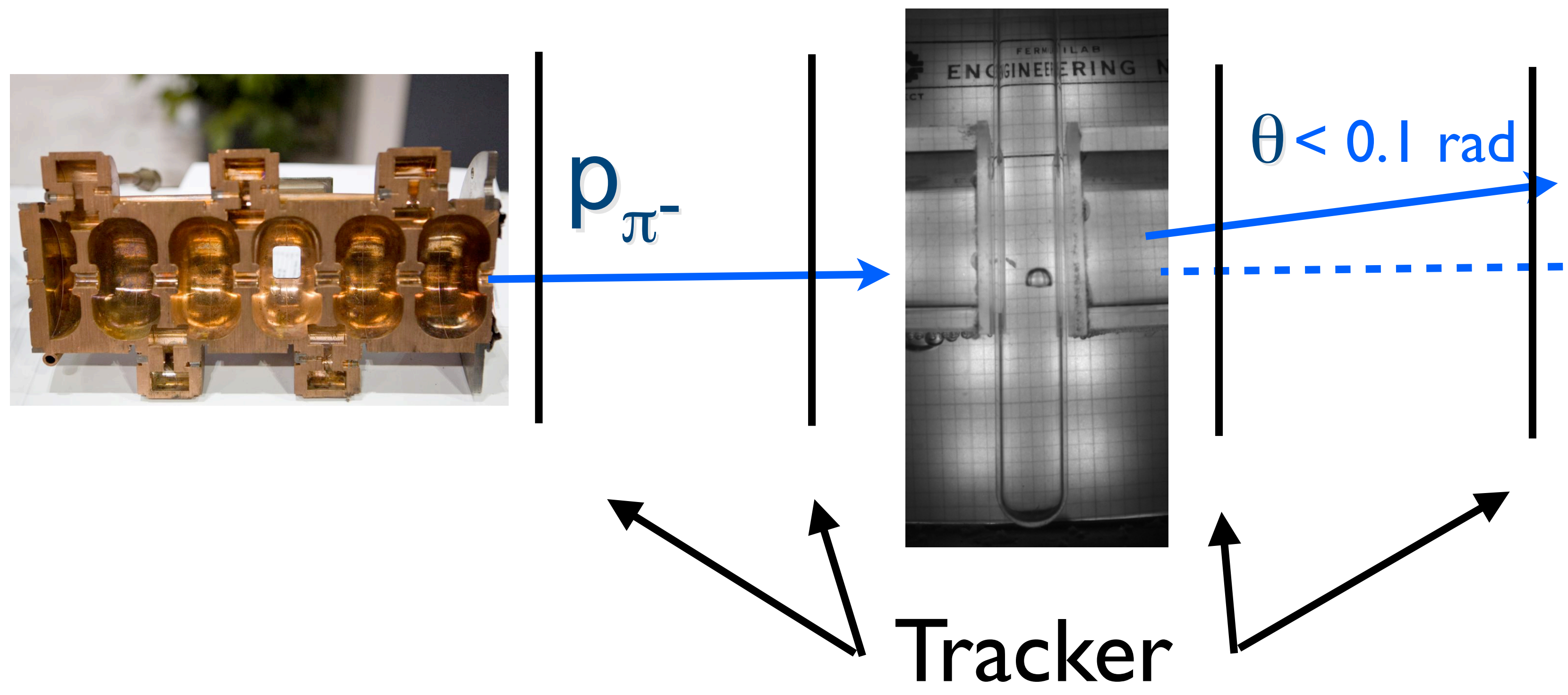
- Bubble chambers are insensitive to MIPs
  - Elastic scattering of charged particles can be tracked with very high precision



$$T = E_{recoil} = \frac{(p\theta)^2}{2m_r}$$

COUPP Iodine Recoil Threshold Experiment

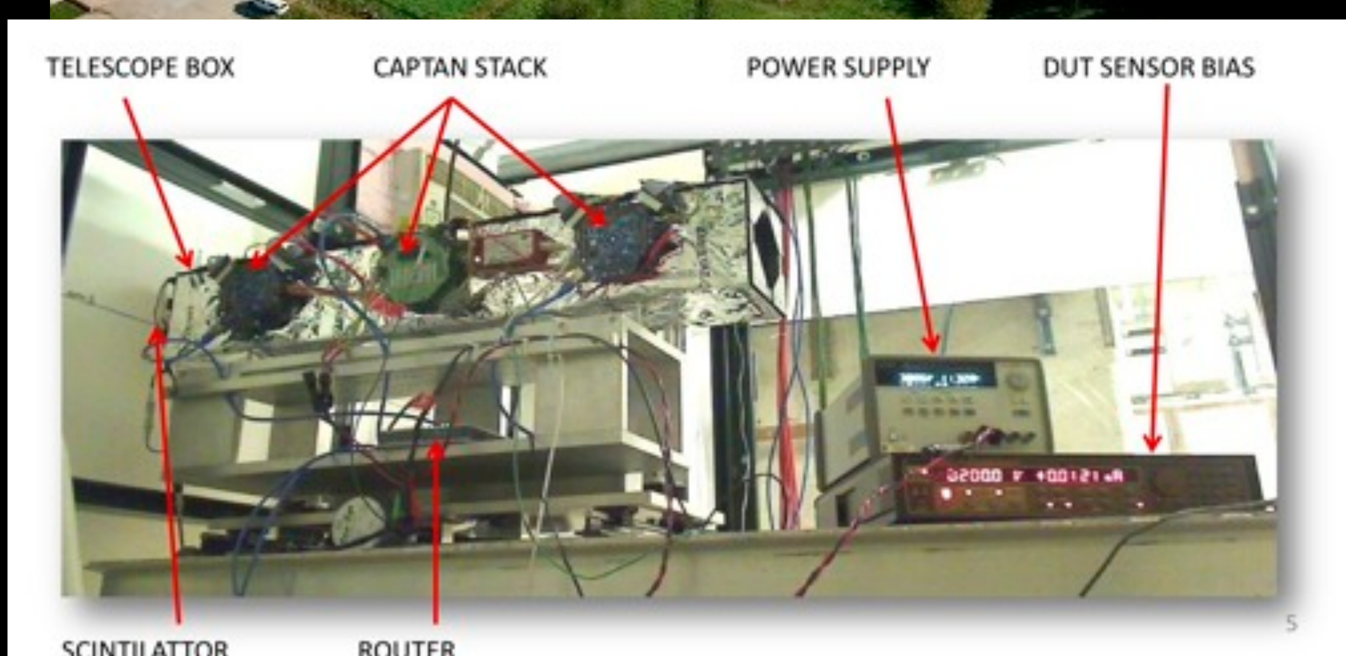
- Provides event by event energy information bubble chambers normally can't provide
- 75% of elastic scattering events with 12 GeV pions at energies relevant to dark matter involve iodine



$$T = E_{recoil} = \frac{(p\theta)^2}{2m_r}$$

COUPP Iodine Recoil Threshold Experiment

- Test beam at Fermilab with a silicon pixel telescope
- Designed a new test tube sized bubble chamber

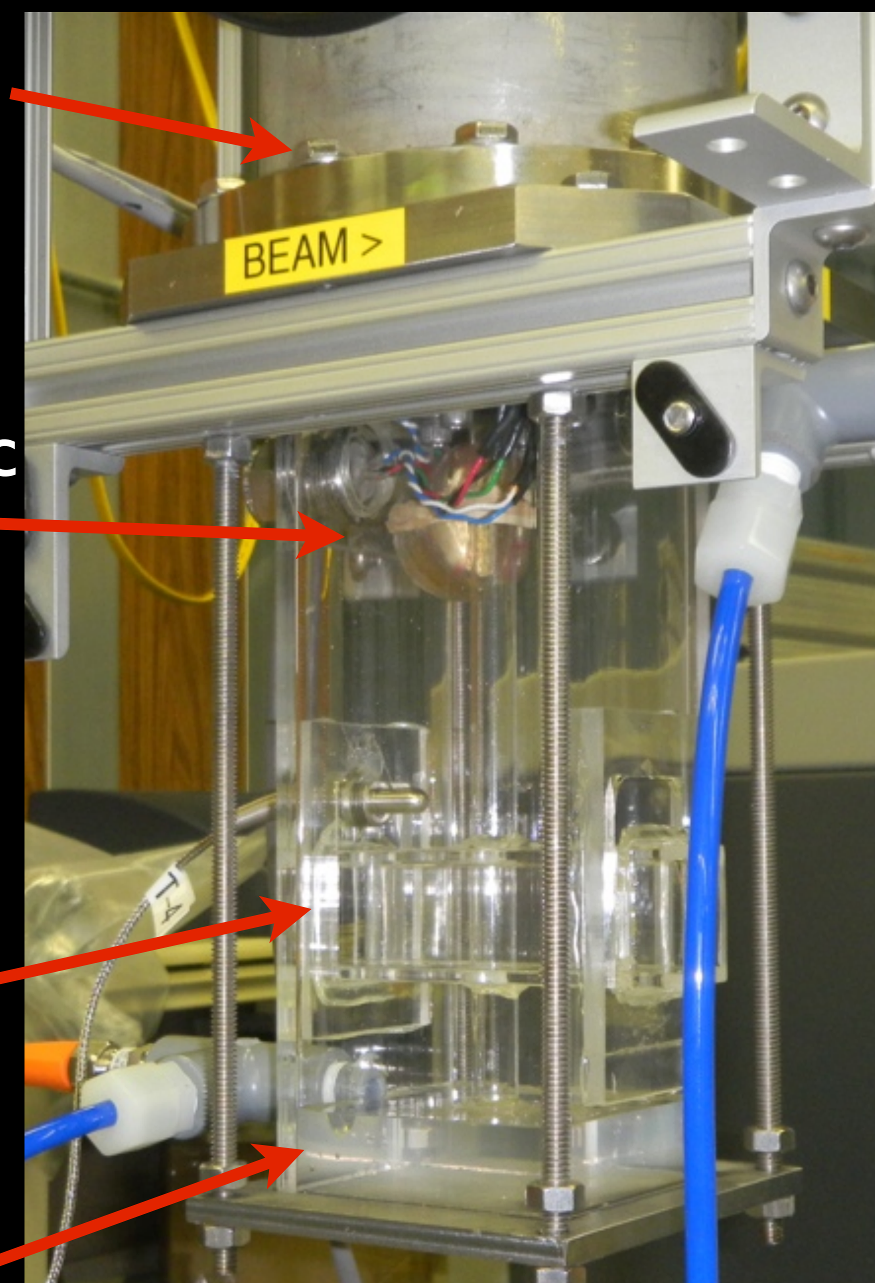


Hydraulics

Piezo-acoustic sensor

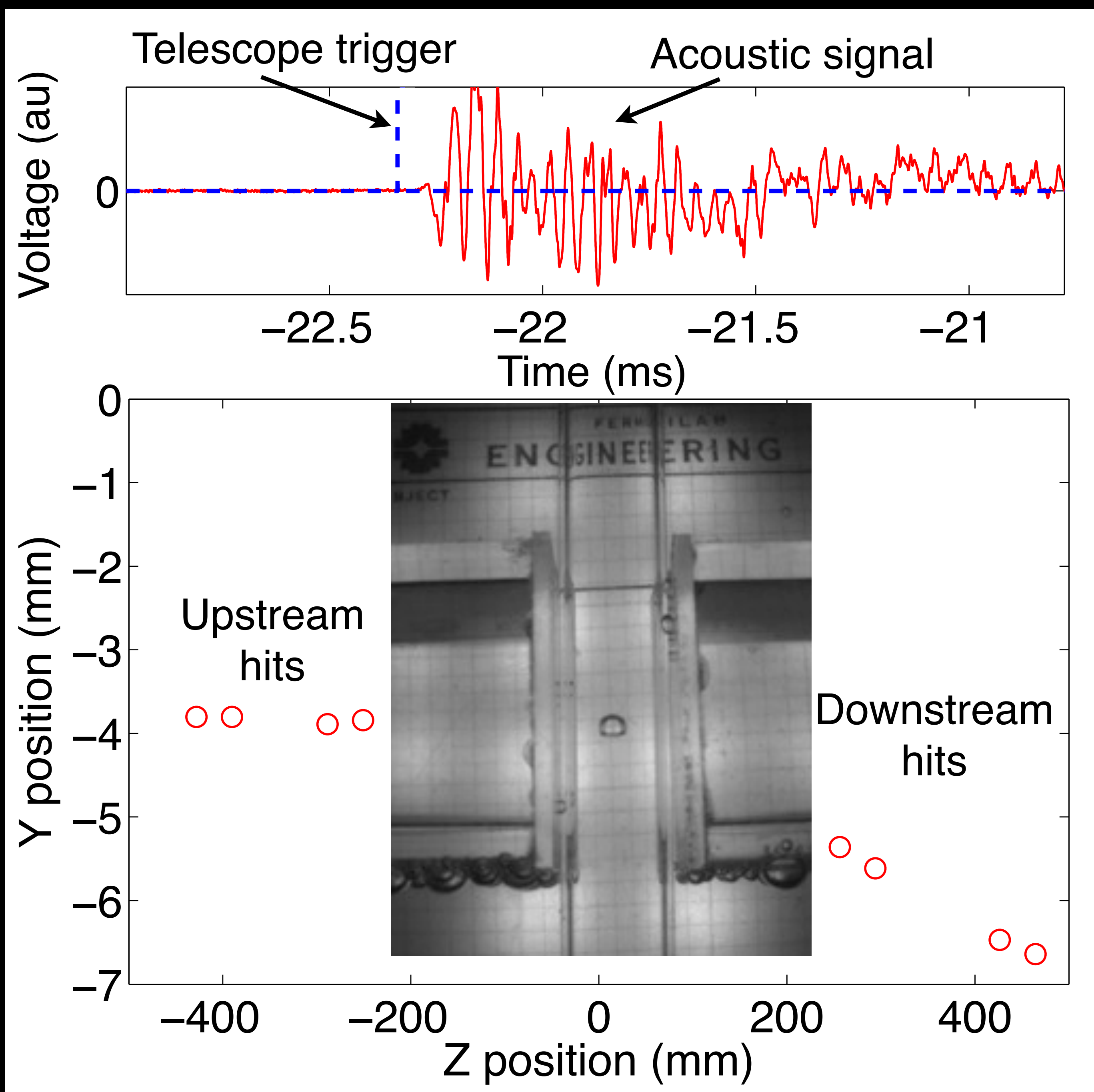
Beam tube

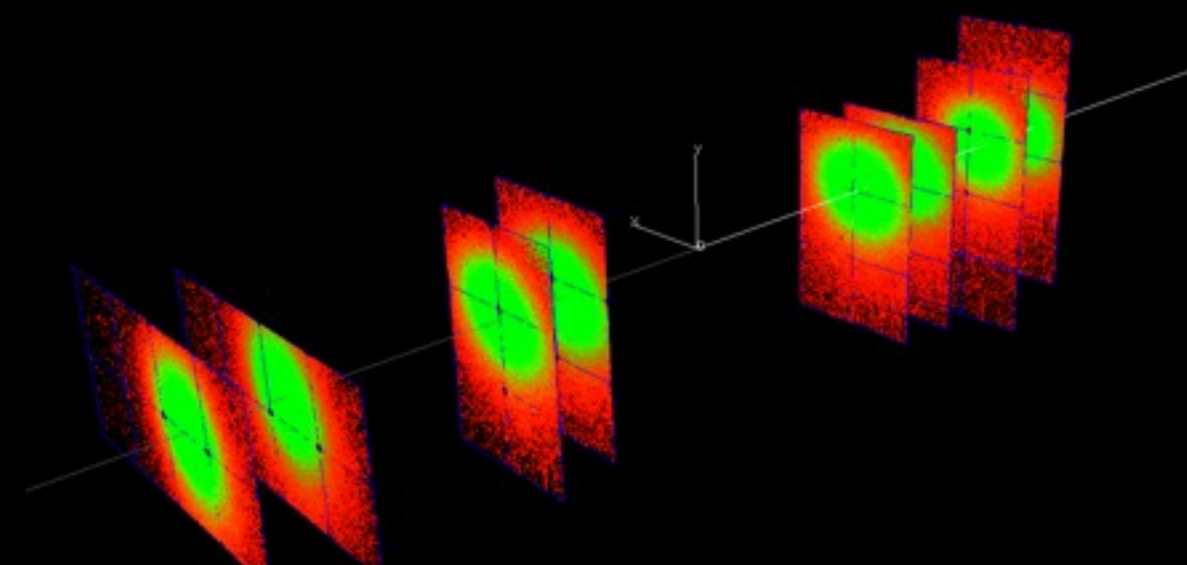
Water bath

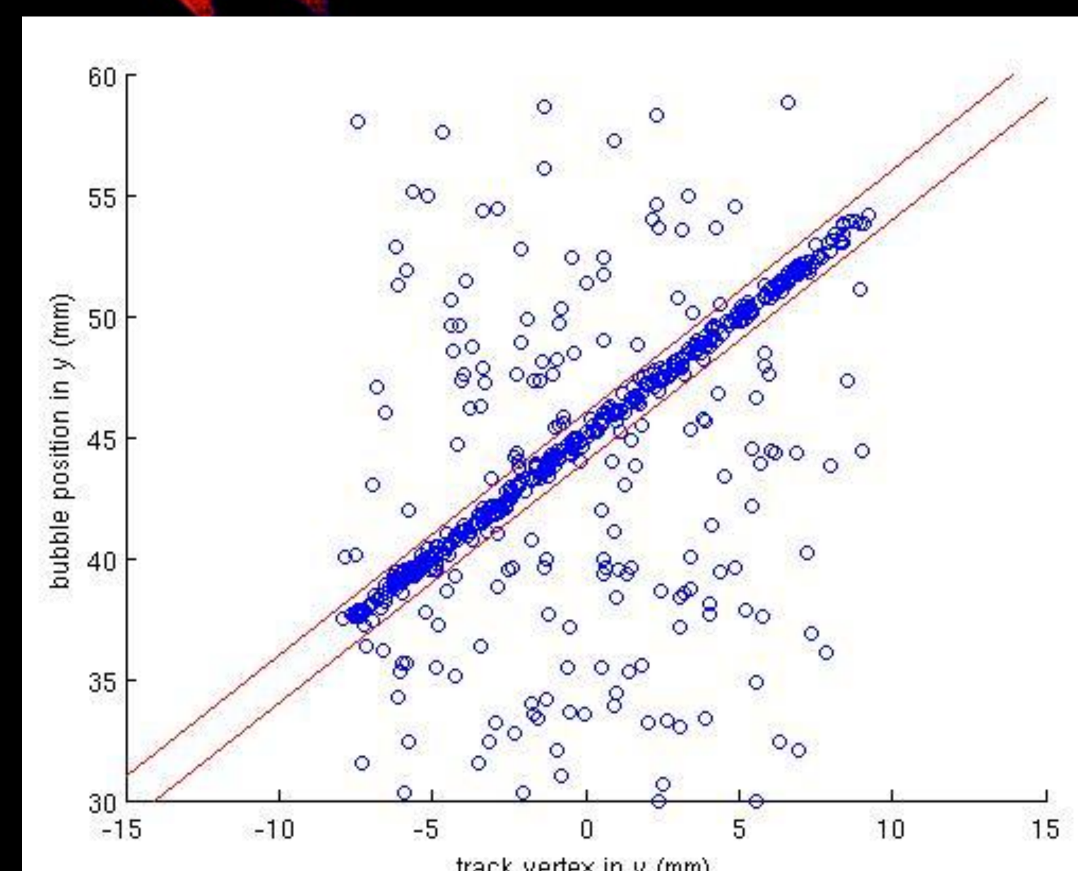


COUPP Iodine Recoil Threshold Experiment

- Beam run at Fermilab in March, 2012

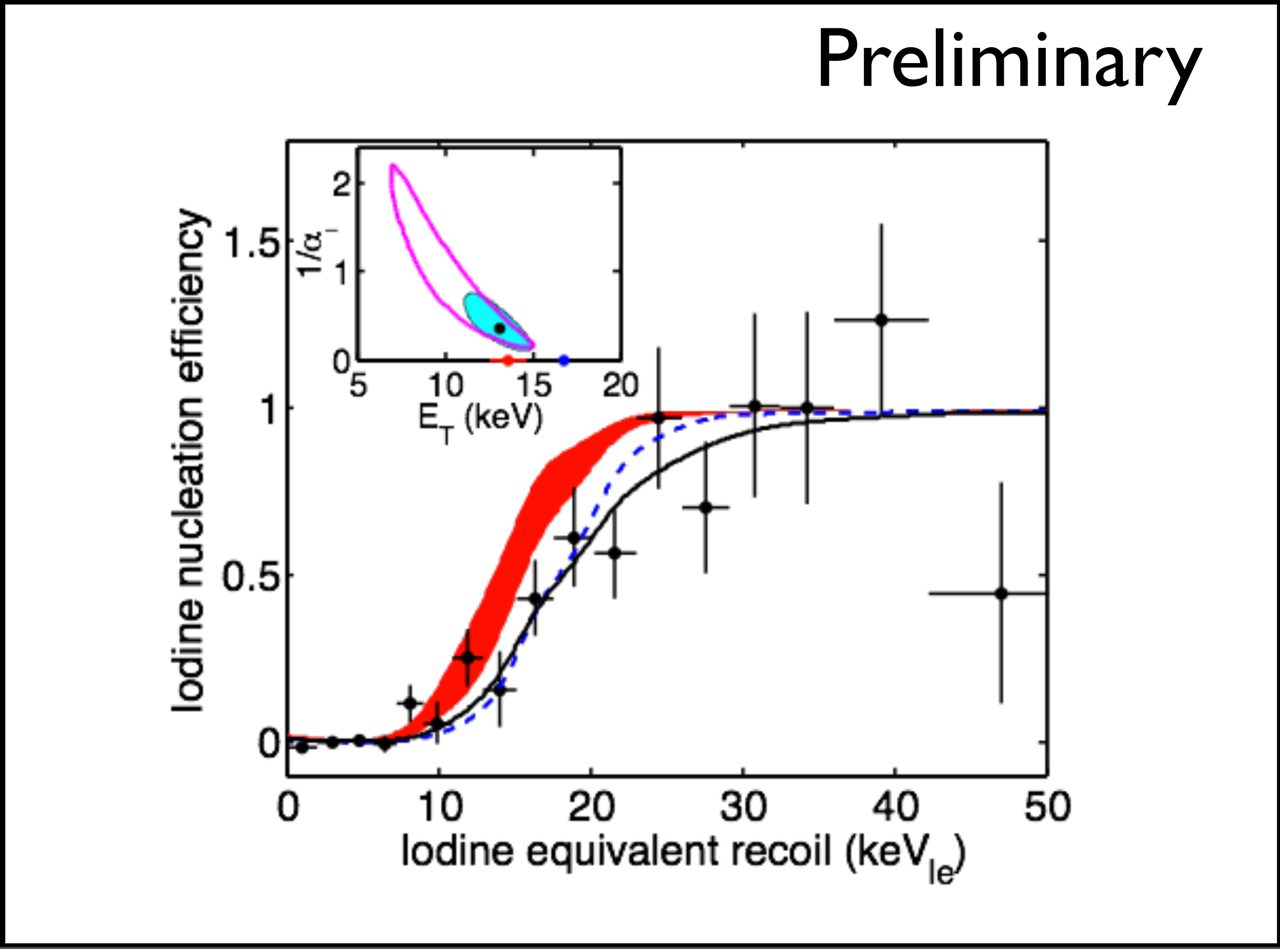






COUPP Iodine Recoil Threshold Experiment

- Analysis shows that iodine threshold is very close to a step function at the predicted energy
  - Limited by resolution (MCS) and statistics

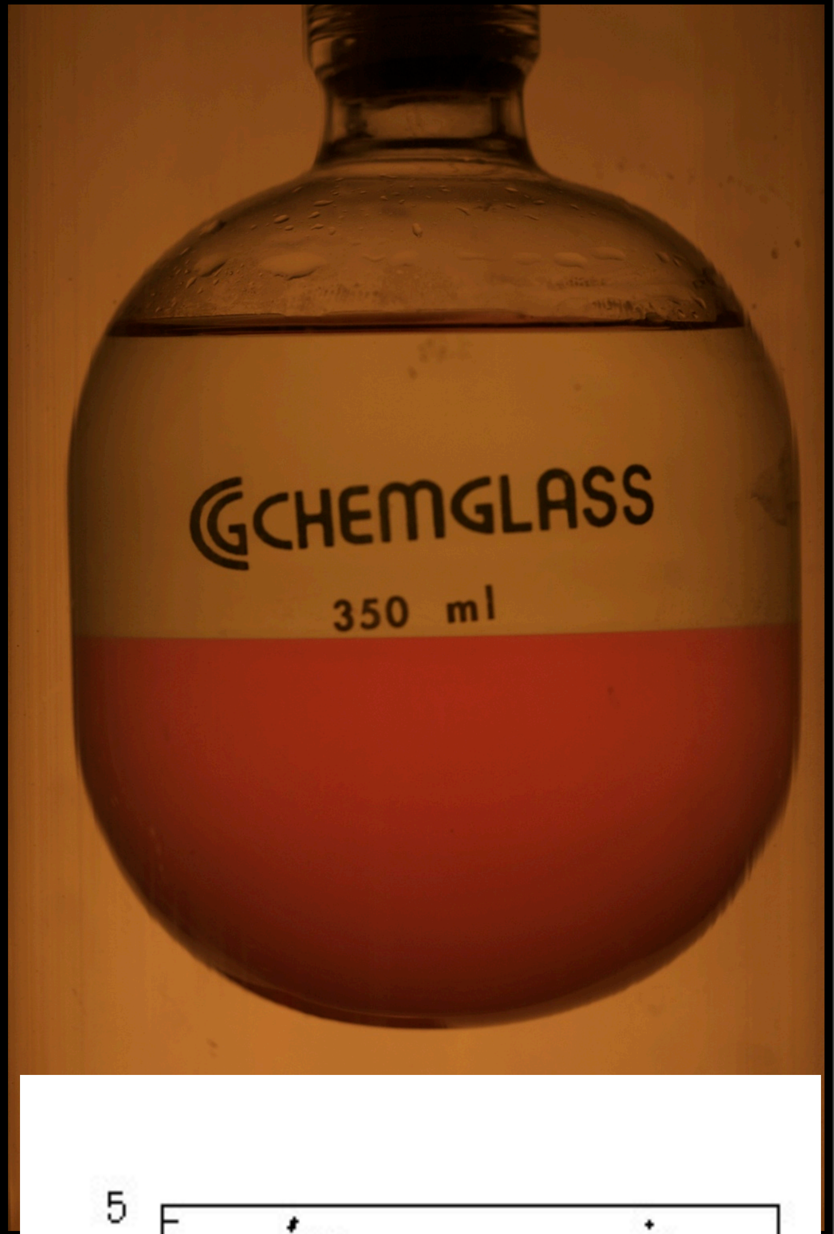


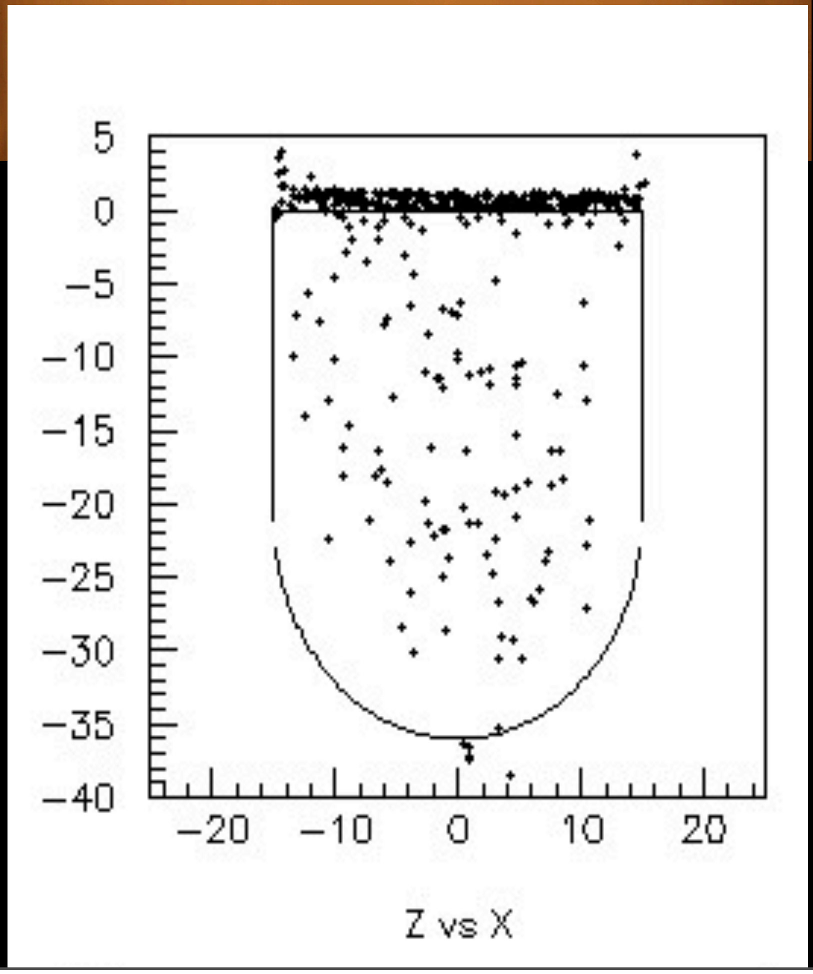
COUPP60

- Engineering run at shallow site in 2010
  - Low backgrounds and acoustic discrimination

COUPP60

- Engineering run at shallow site in 2010
  - Low backgrounds and acoustic discrimination
  - Fluid darkening due to photodissociation of iodine
  - Excessive surface rate





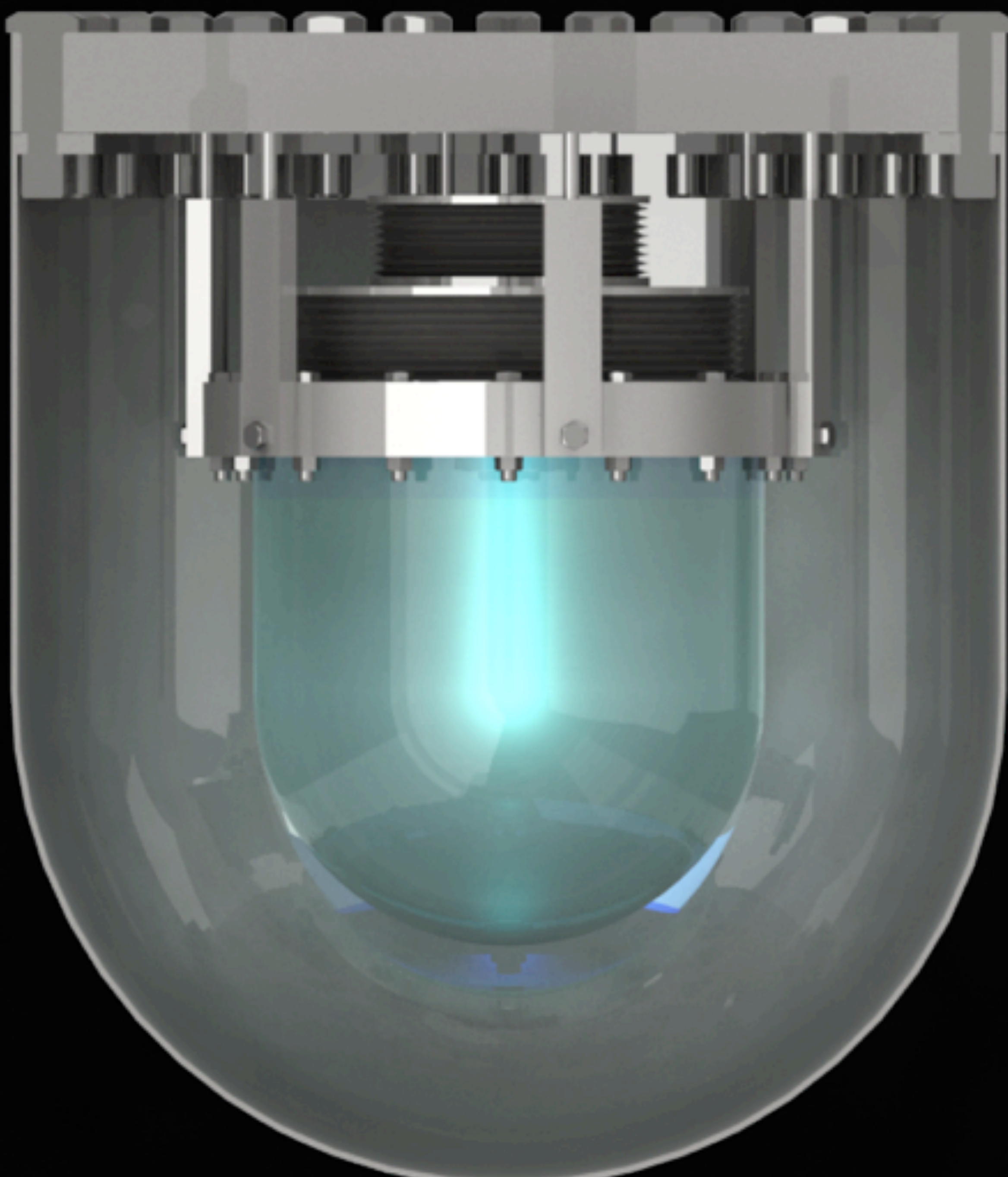
COUPP60

- Engineering run at shallow site in 2010
  - Low backgrounds and acoustic discrimination
  - Fluid darkening due to photodissociation of iodine
  - Excessive surface rate
- Solutions tested in second run November, 2011
- Moving to SNOLAB since last summer


CYLINDER
EMPTY
IN USE


Running by
end of month?

COUPP500 (or EREBOS-500)

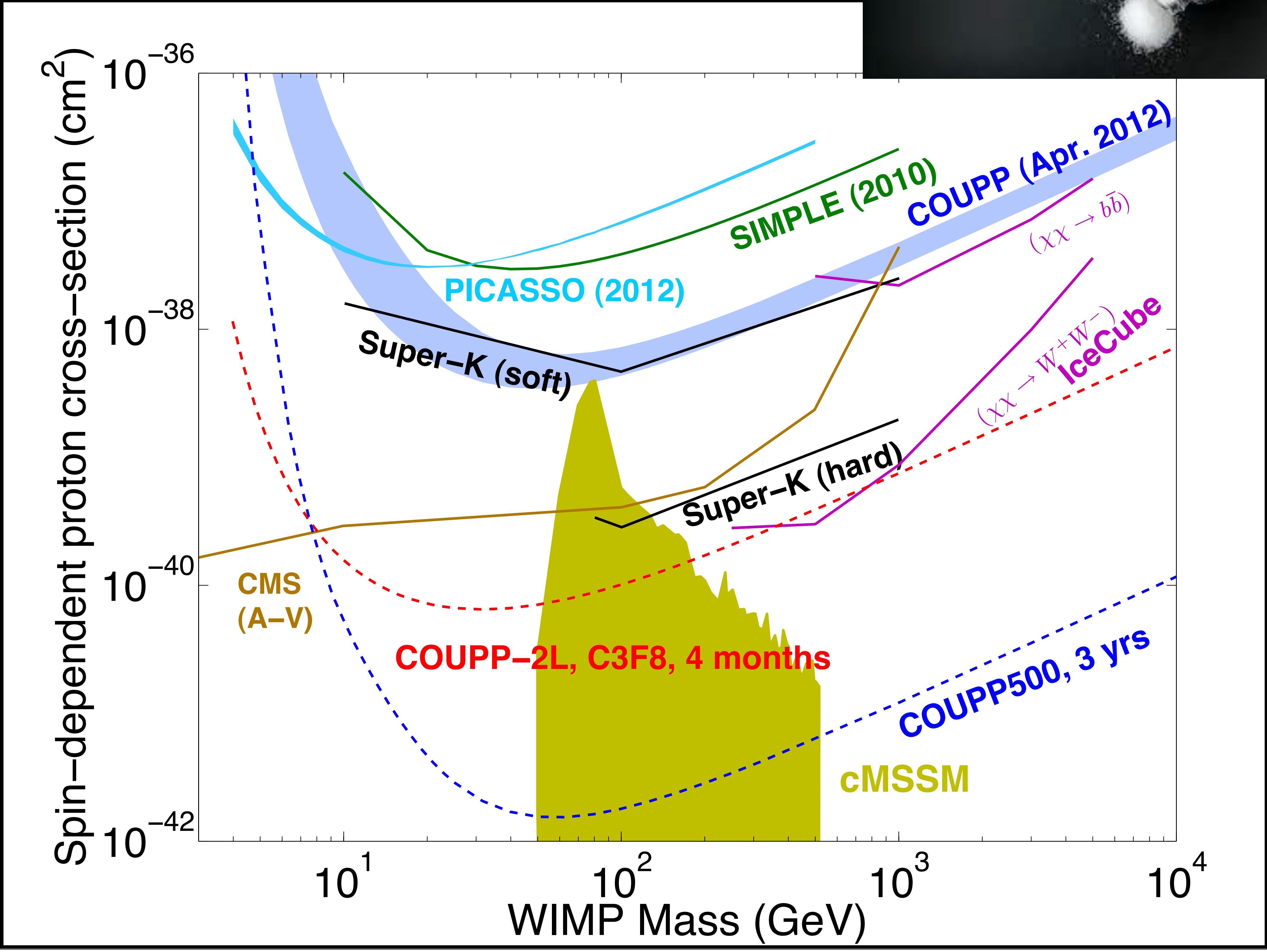


- New merger with Canadian PICASSO collaboration (recent vote chose EREBOS as the new name)
- Funded by NSF and DOE as part of G2 (big showdown in October?)
- Engineering well underway
- Construction 2014-2015?

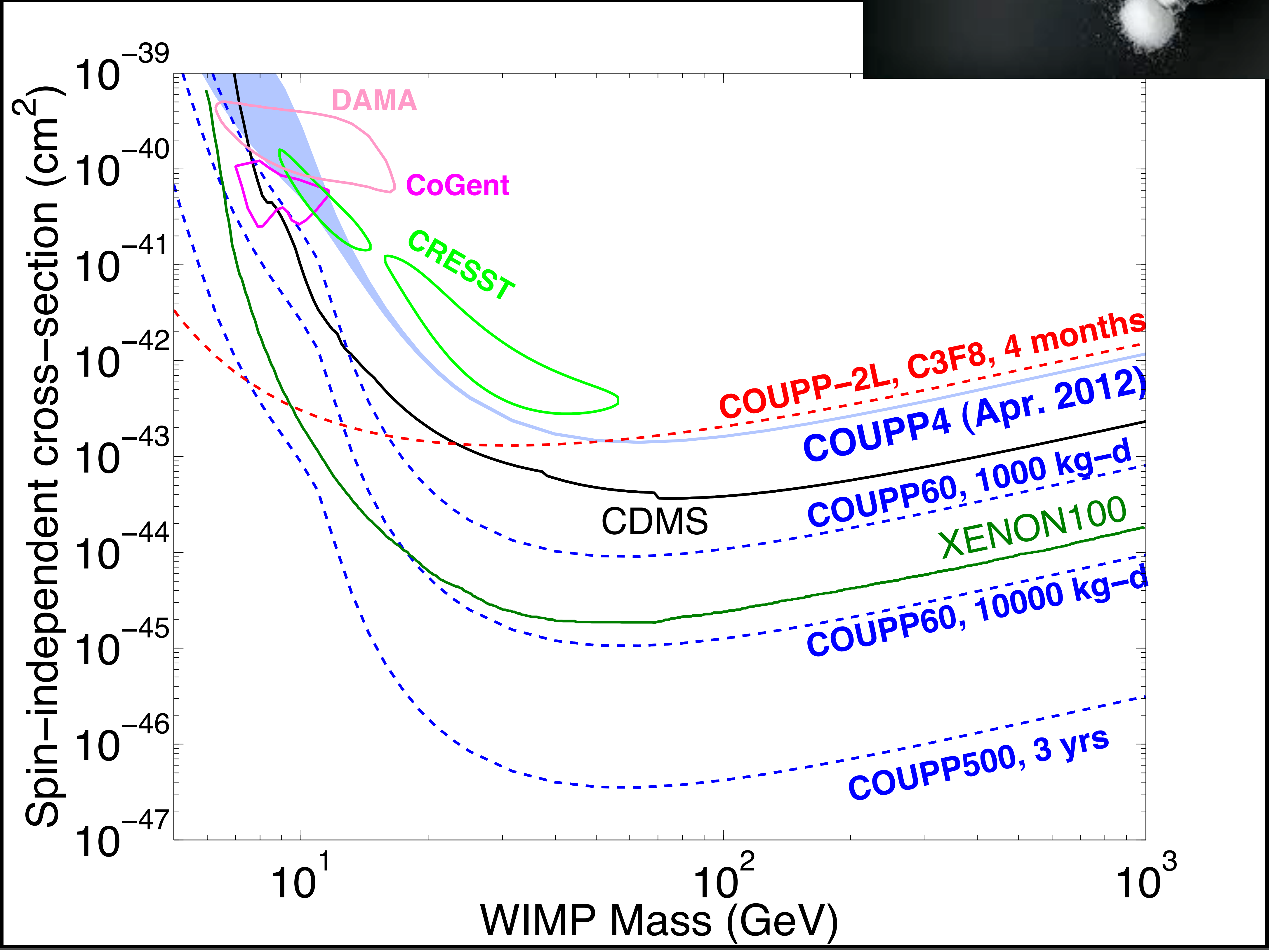
COUPP4 redux

- Alternate fluid - remove the iodine - C_3F_8
  - Lower threshold (down to 3 keV in test stand)
  - Improved sensitivity at low WIMP mass
  - Improved SD sensitivity
- First effort in concert with the PICASSO collaboration
- Possible use in COUPP500 chamber

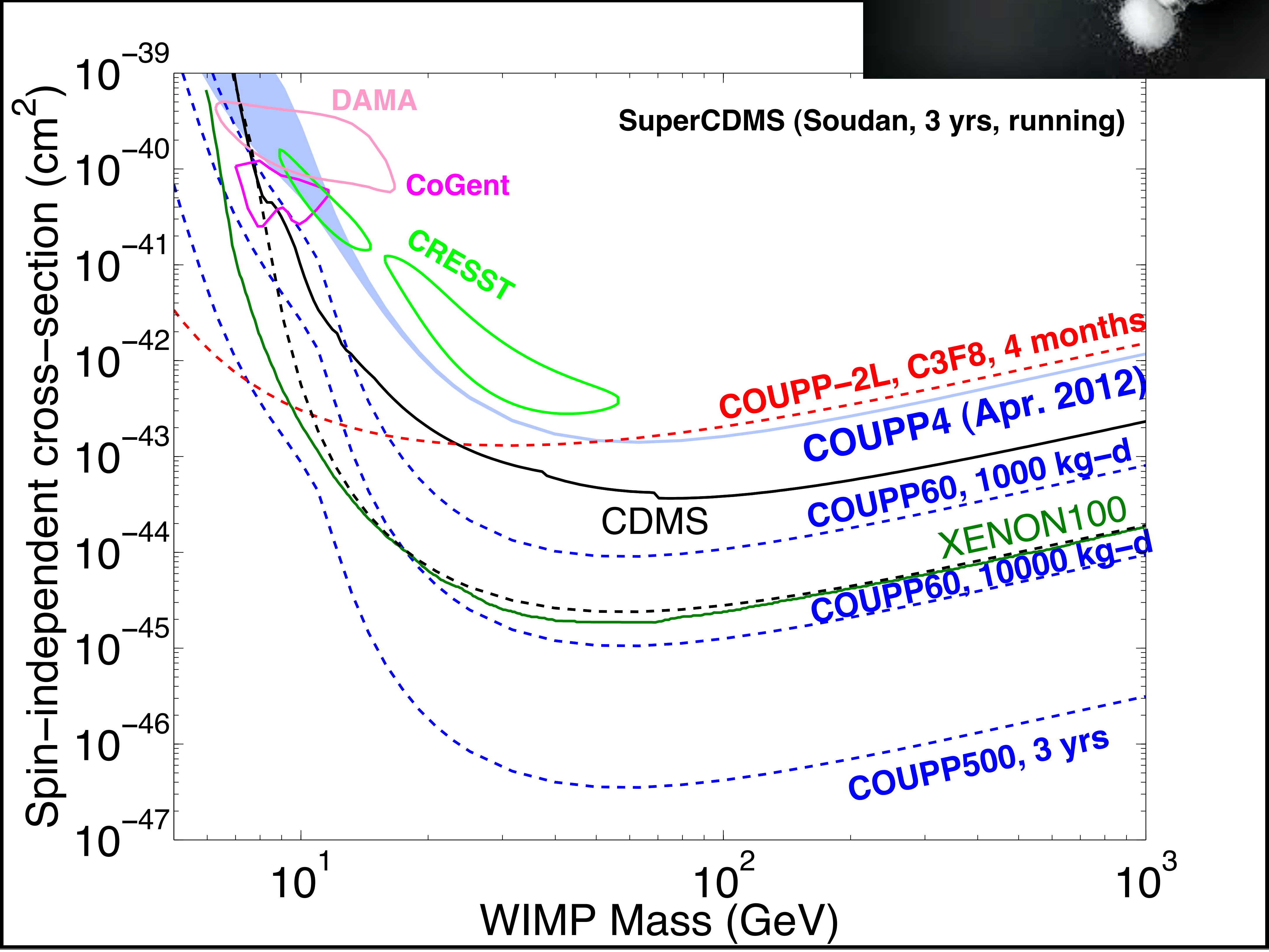
Projections



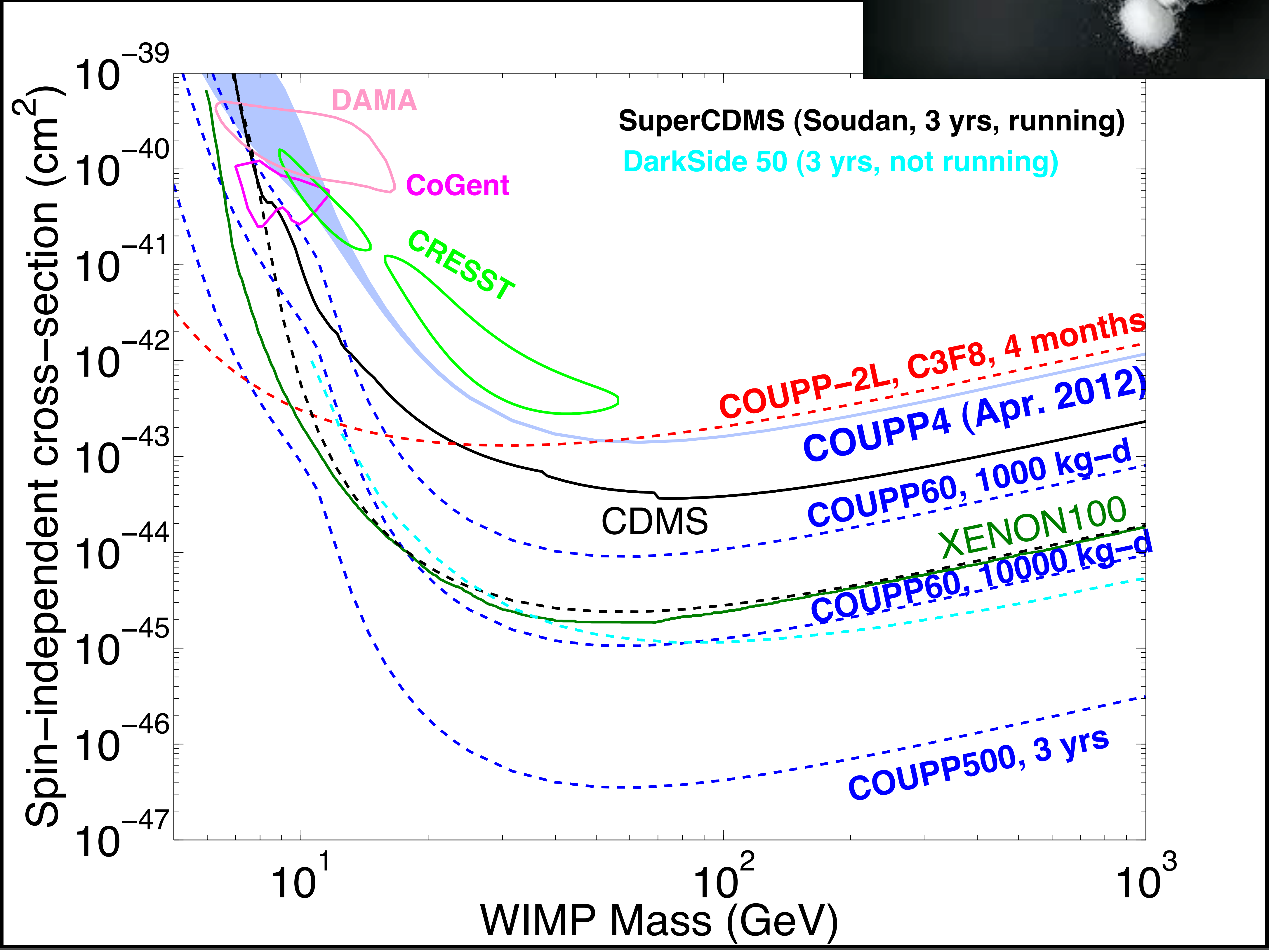
Projections



Projections

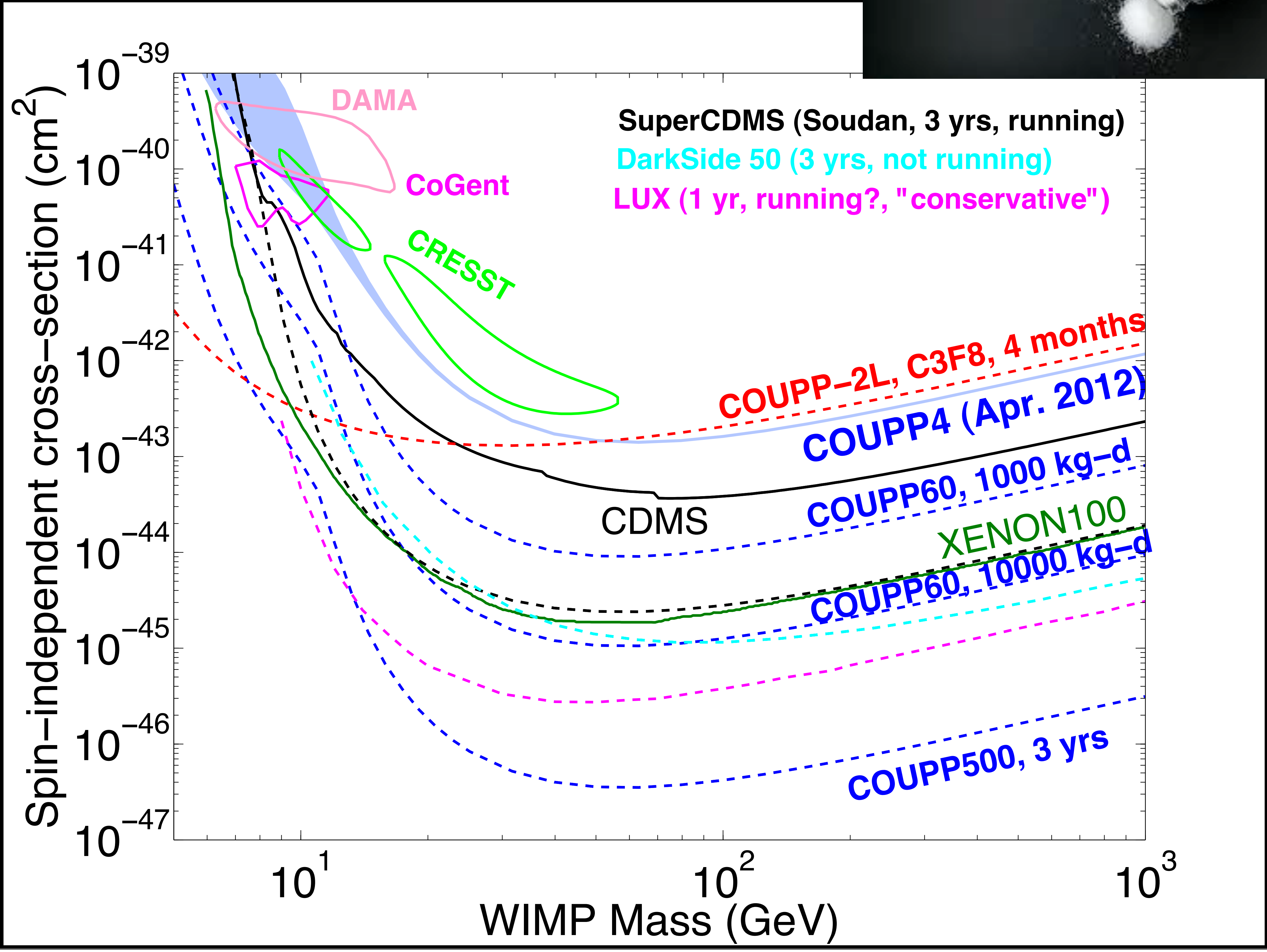


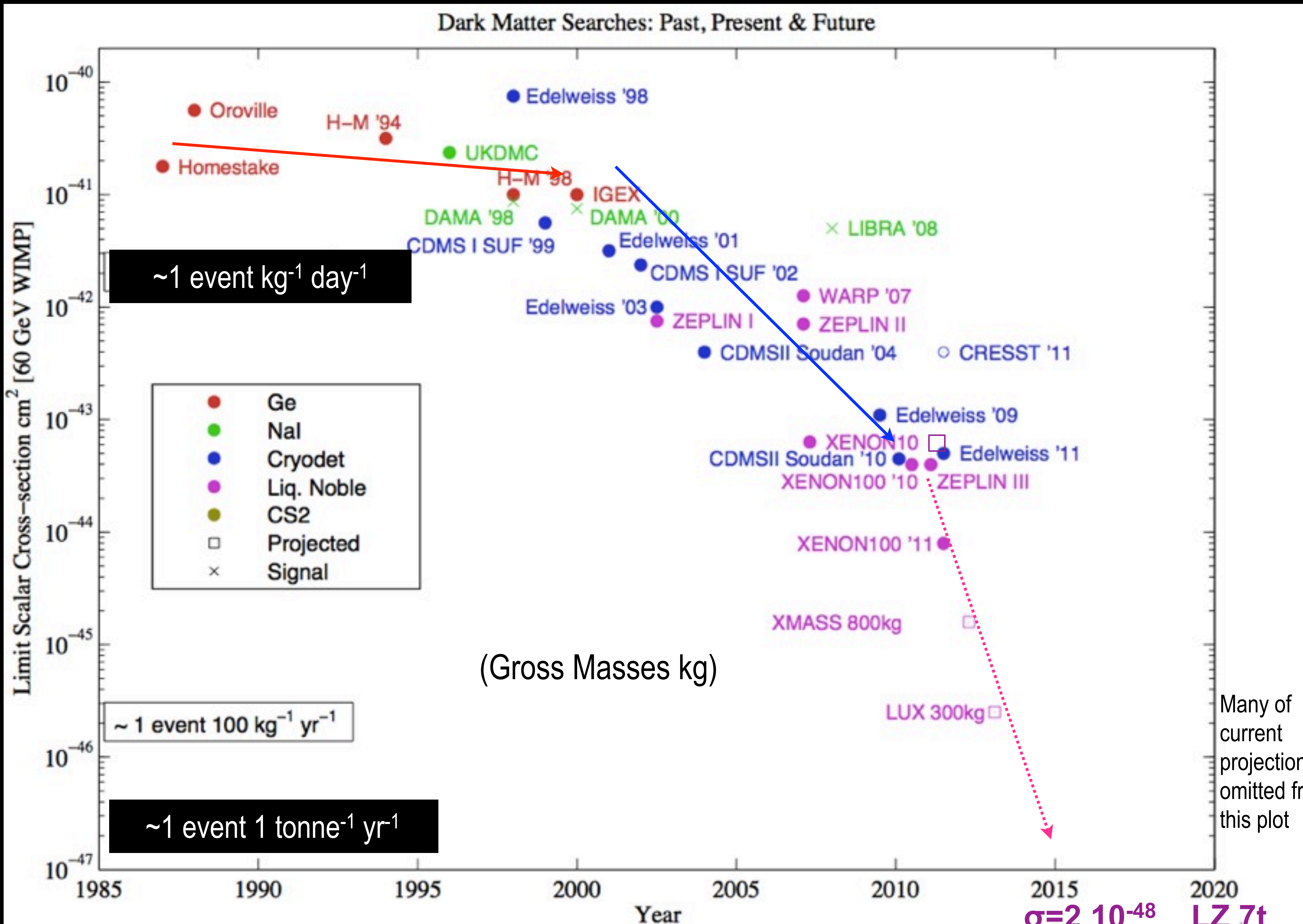
Projections



Tuesday, April 16, 2013

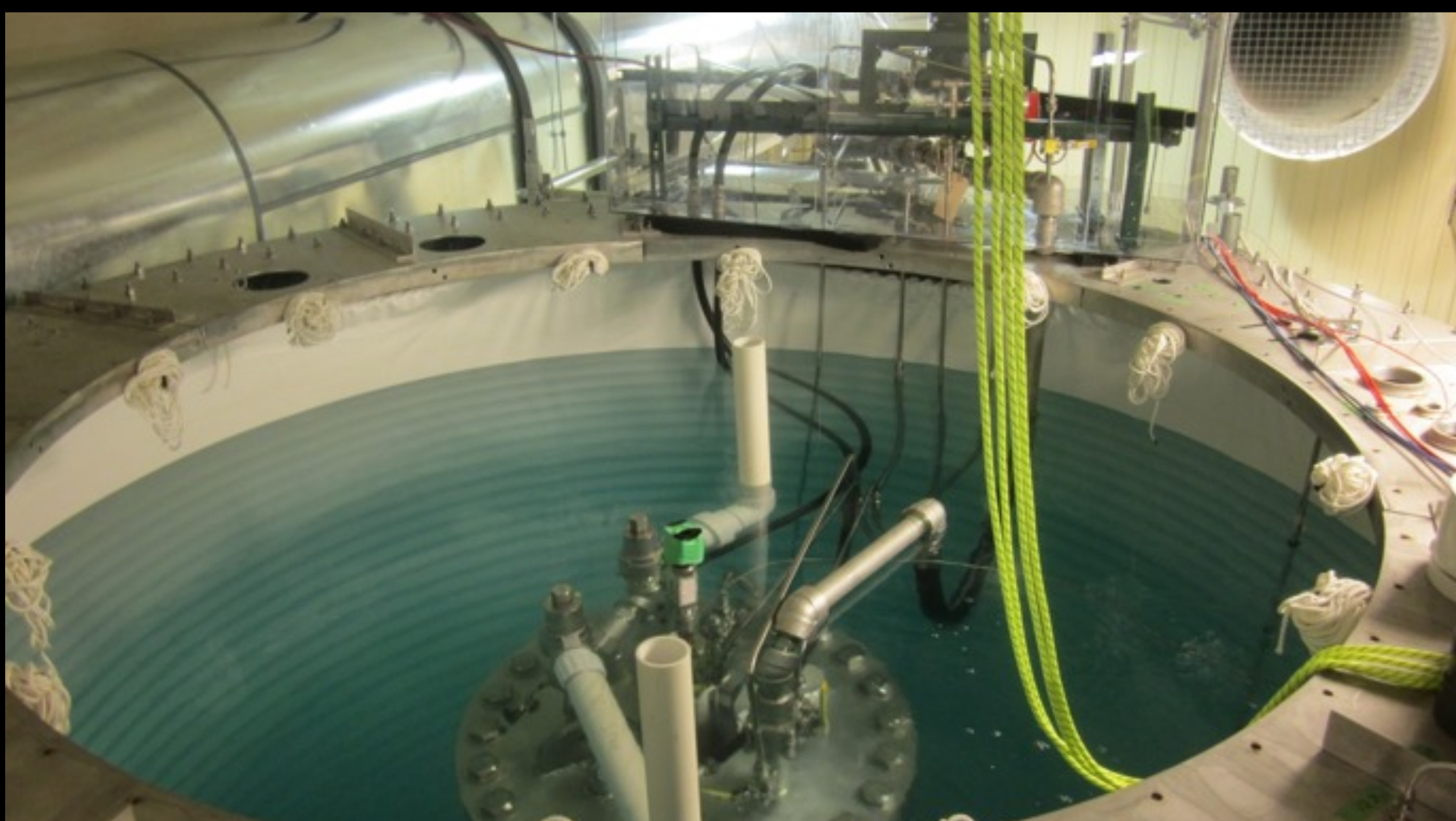
Projections

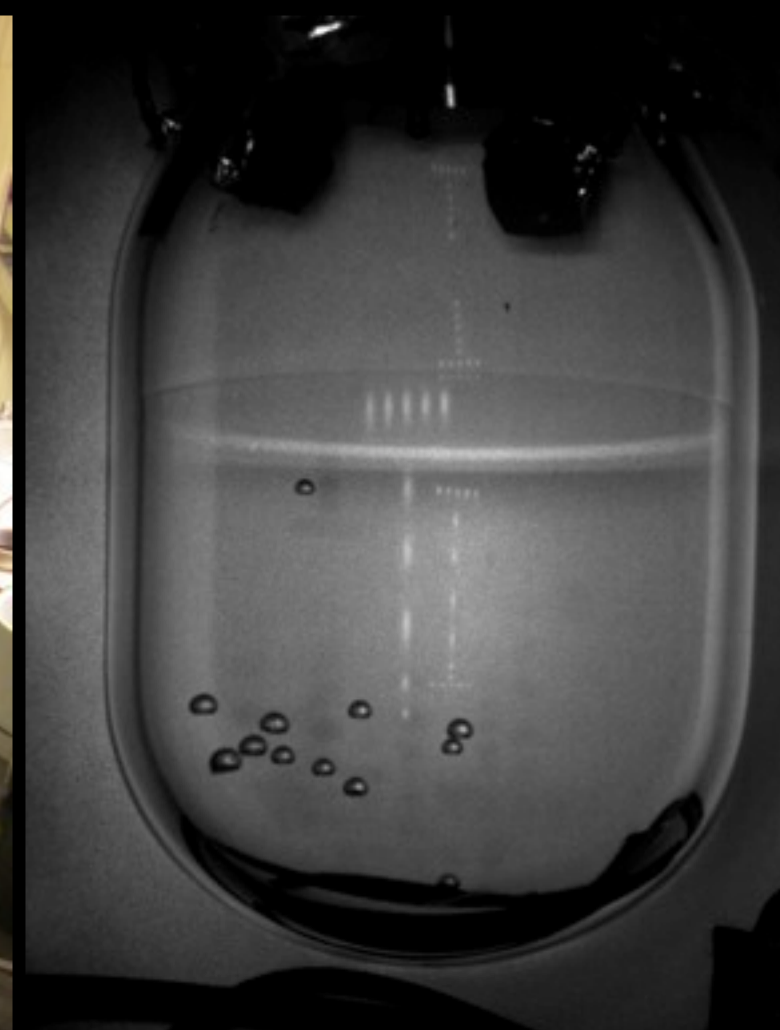



Dark Matter Searches: Past, Present & Future
Limit Scalar Cross−section cm^2 [60 GeV WIMP]
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
Year
1985
1990
1995
2000
2005
2010
2015
2020
Oroville
Homestake
H–M '94
UKDMC
Edelweiss '98
H–M '98
IGEX
DAMA '98
DAMA '00
CDMS I SUF '99
Edelweiss '01
CDMS I SUF '02
LIBRA '08
Edelweiss '03
ZEPLIN I
WARP '07
ZEPLIN II
CDMSII Soudan '04
CRESST '11
Edelweiss '09
XENON10
CDMSII Soudan '10
Edelweiss '11
XENON100 '10
ZEPLIN III
XENON100 '11
XMASS 800kg
LUX 300kg
Ge
NaI
Cryodet
Liq. Noble
CS2
Projected
Signal
~1 event kg^{-1} day^{-1}
~ 1 event 100 kg^{-1} yr^{-1}
~1 event 1 tonne^{-1} yr^{-1}
(Gross Masses kg)
Many of current projections omitted fro this plot
σ=2 10^{-48}
LZ 7t

Conclusion

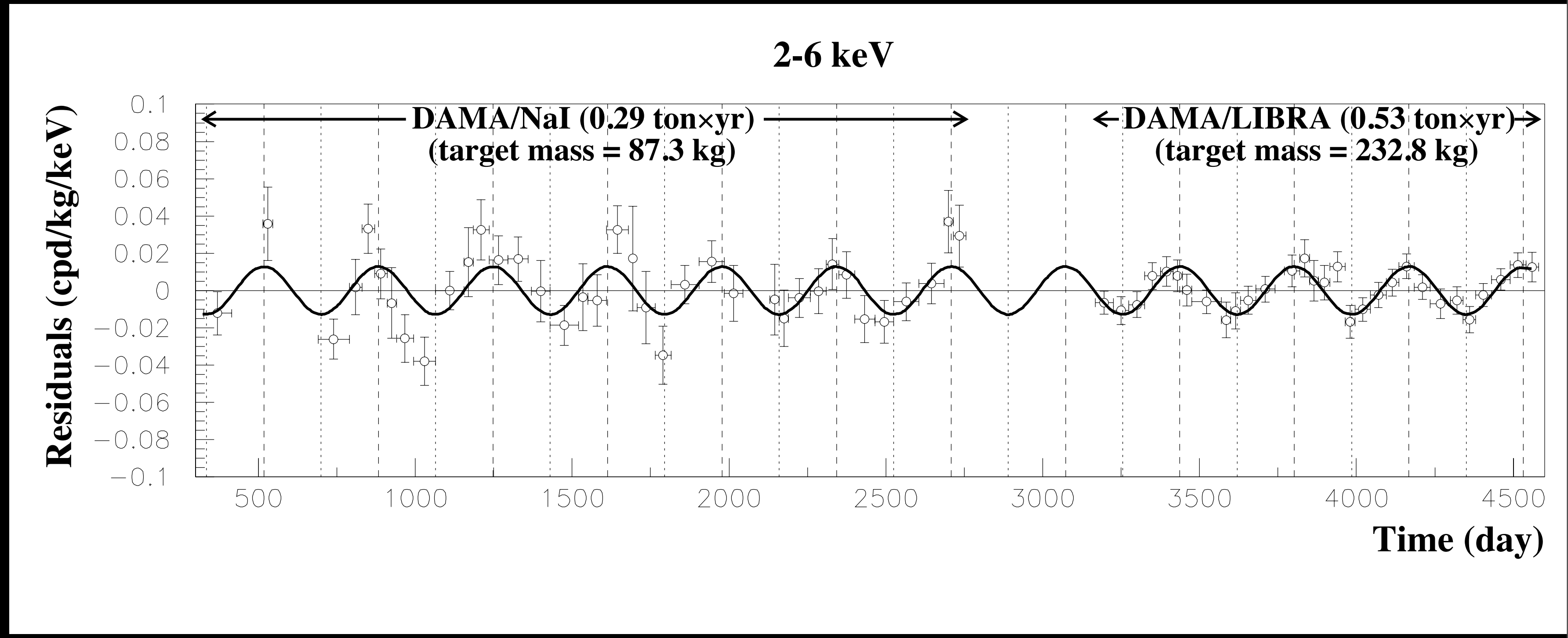
- Dark matter searches are making fast progress (indirect, accelerator and direct)
- COUPP is producing the best direct detection limits on spin-dependent dark matter
- COUPP bubble chambers are also competitive for spin-independent searches





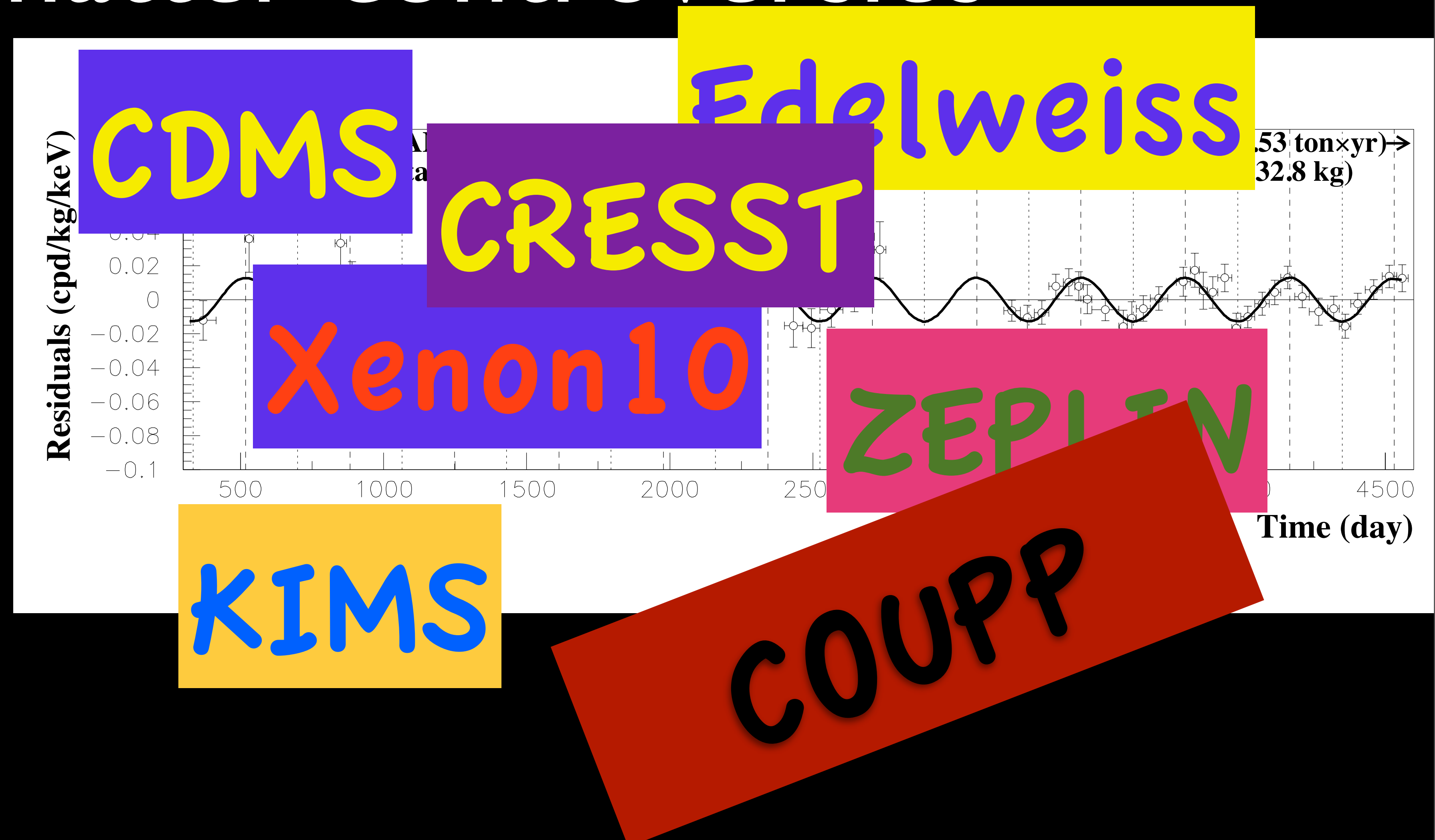
Dark matter controversies

DAMA - positive claim for 10 years!



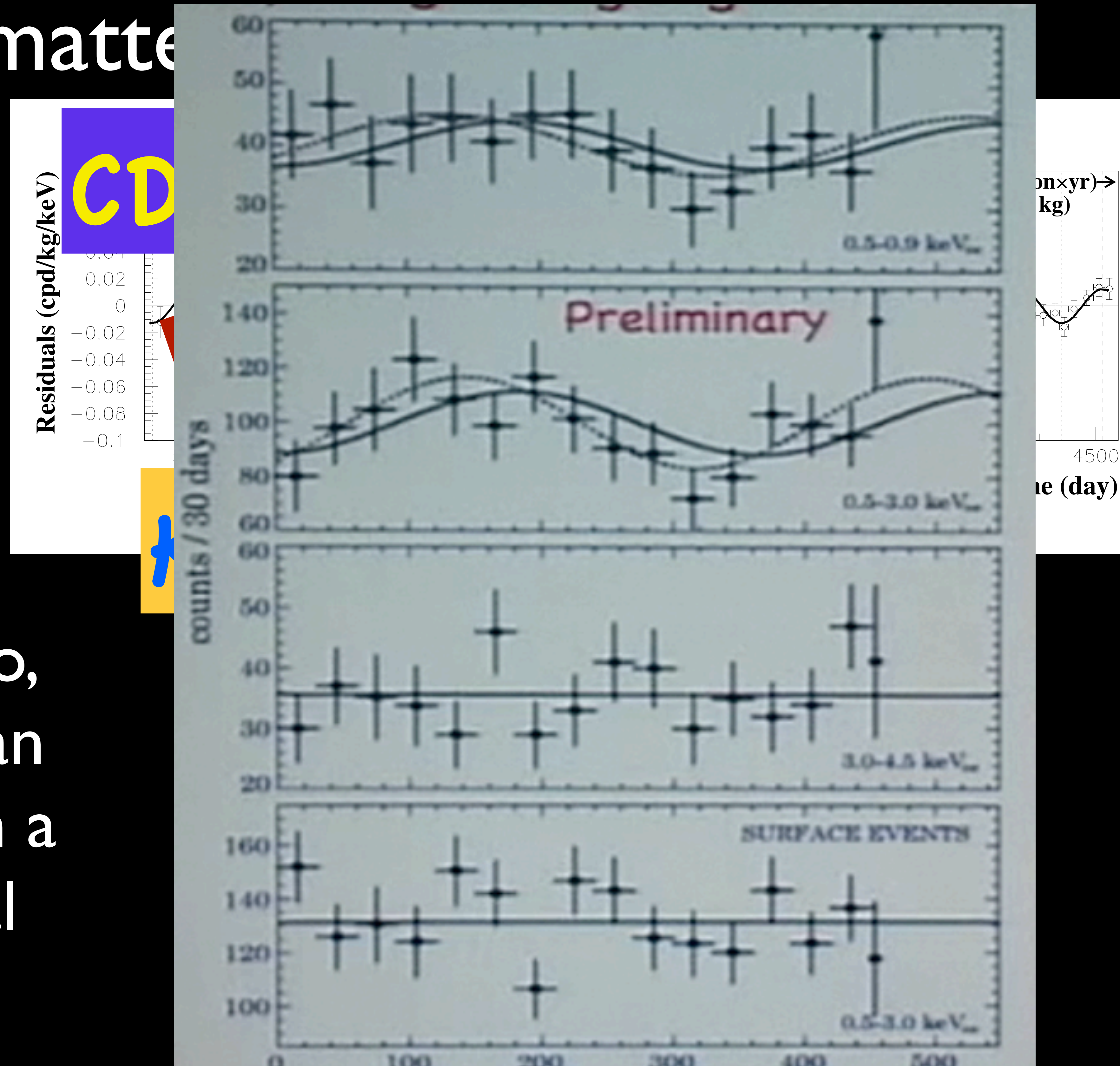
Dark matter controversies

DAMA - positive claim for 10 years!



Dark matte

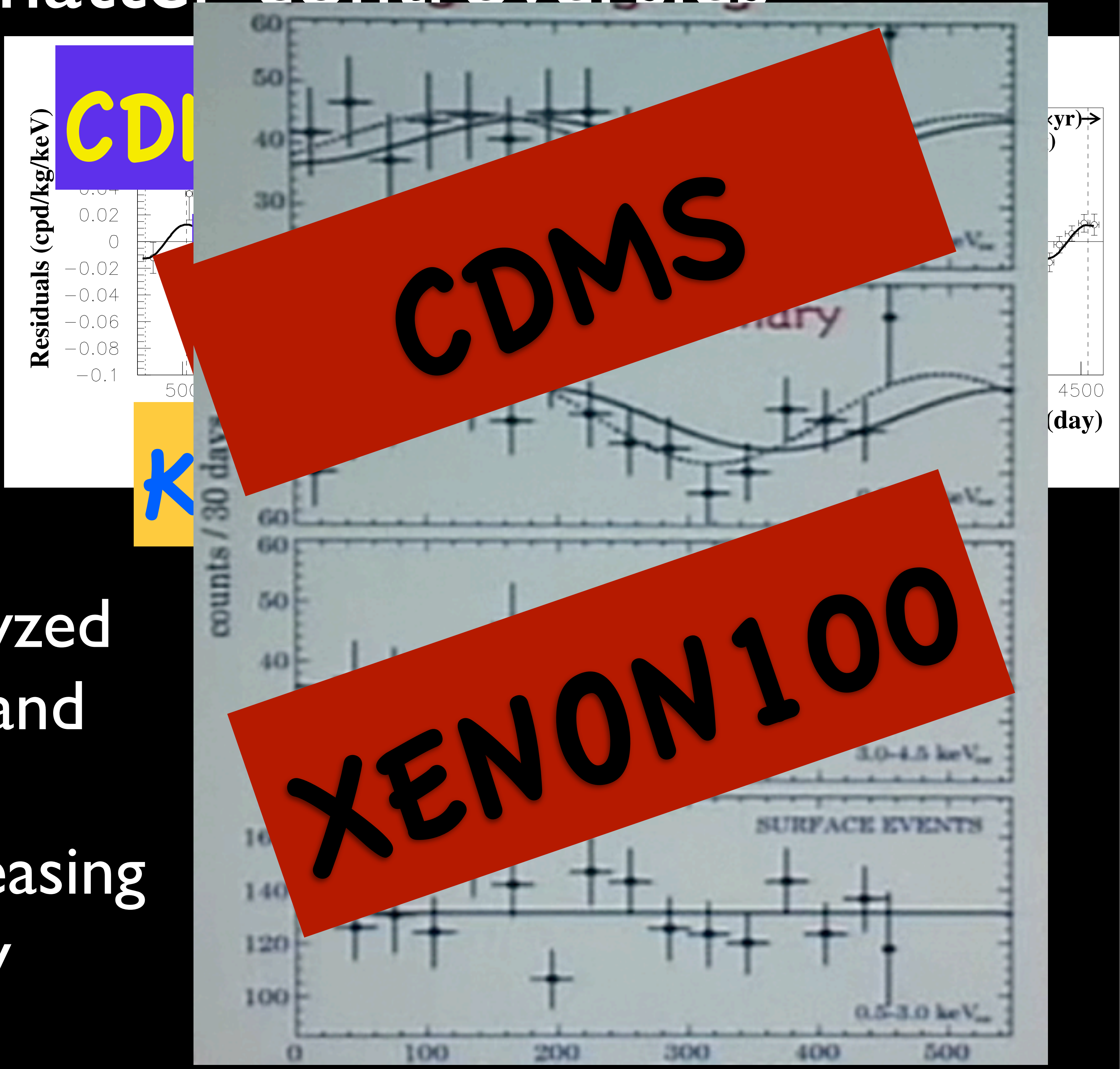
DAMA - positive claim for 10 years!



A few years ago, CoGeNT saw an excess and then a possible annual modulation

Dark matter controversies

DAMA -
positive claim
for 10 years!



CoGeNT reanalyzed their own data and found a new background, decreasing the sensitivity

D... s

DAMA

positive c

for 10 ye

Recently,

(run by m

an excess

possib

n

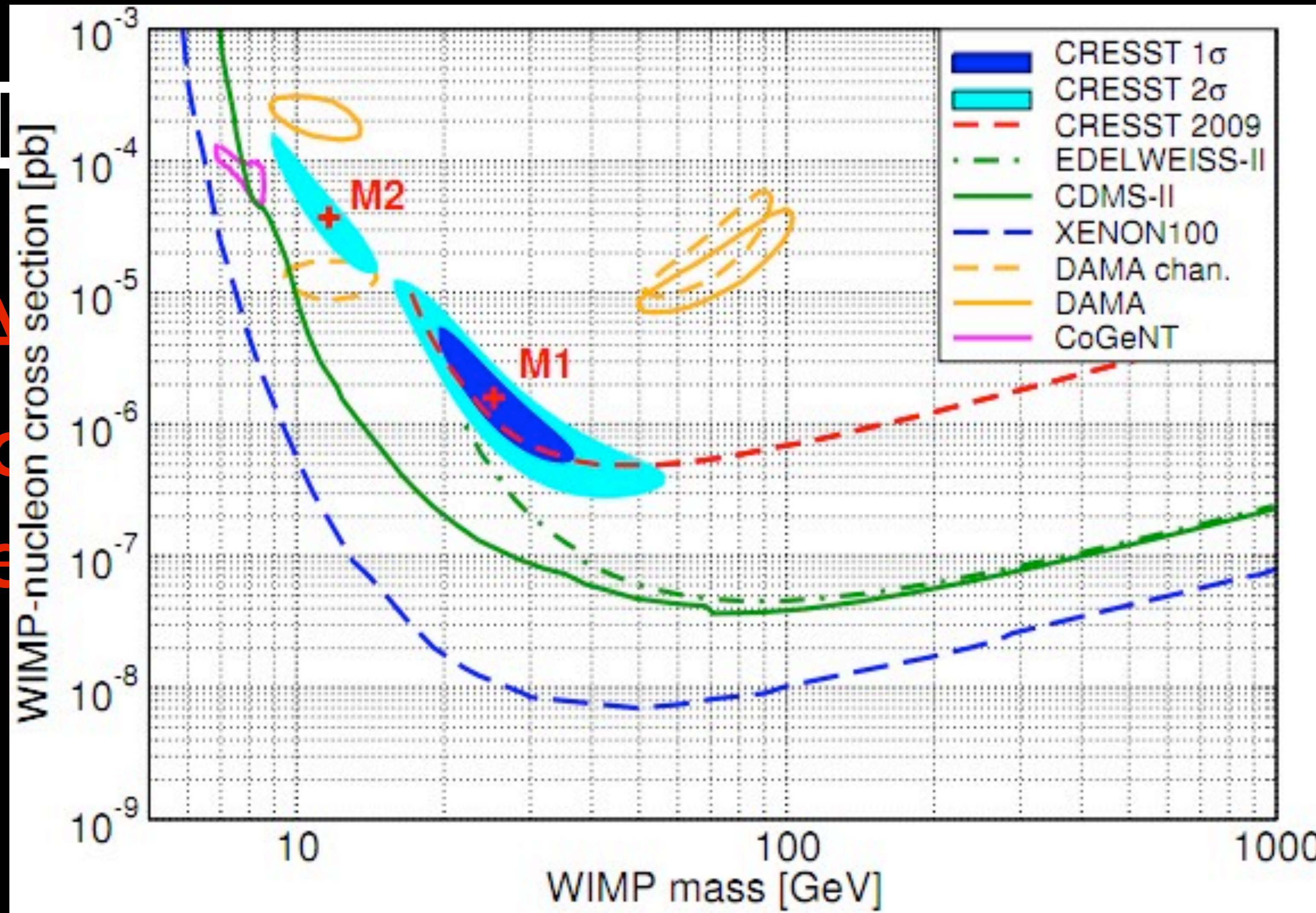
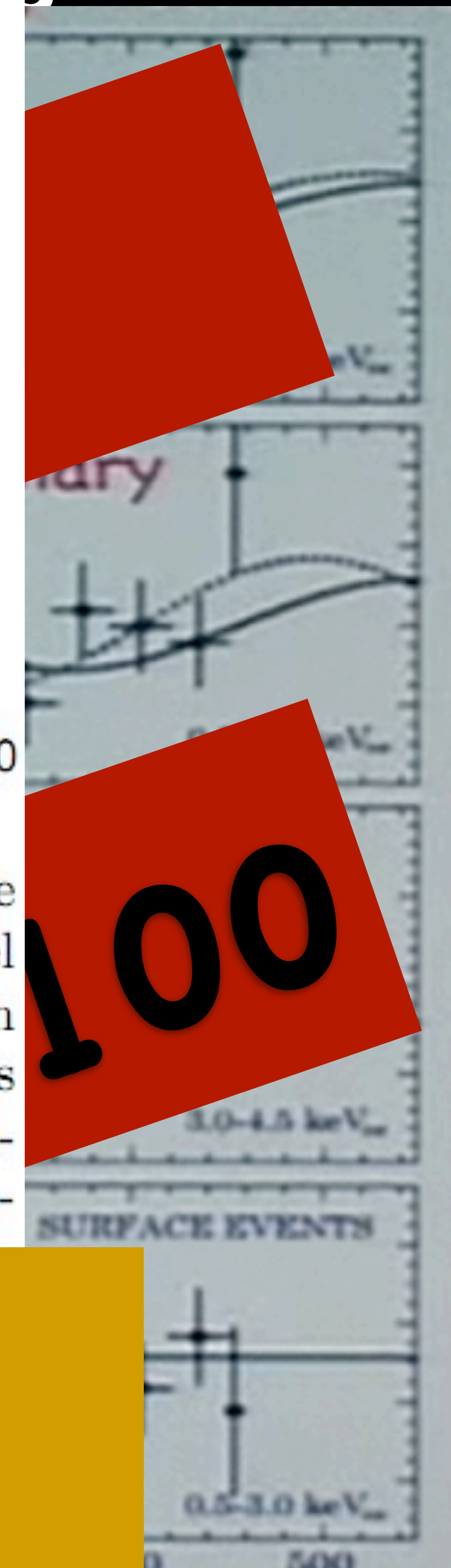
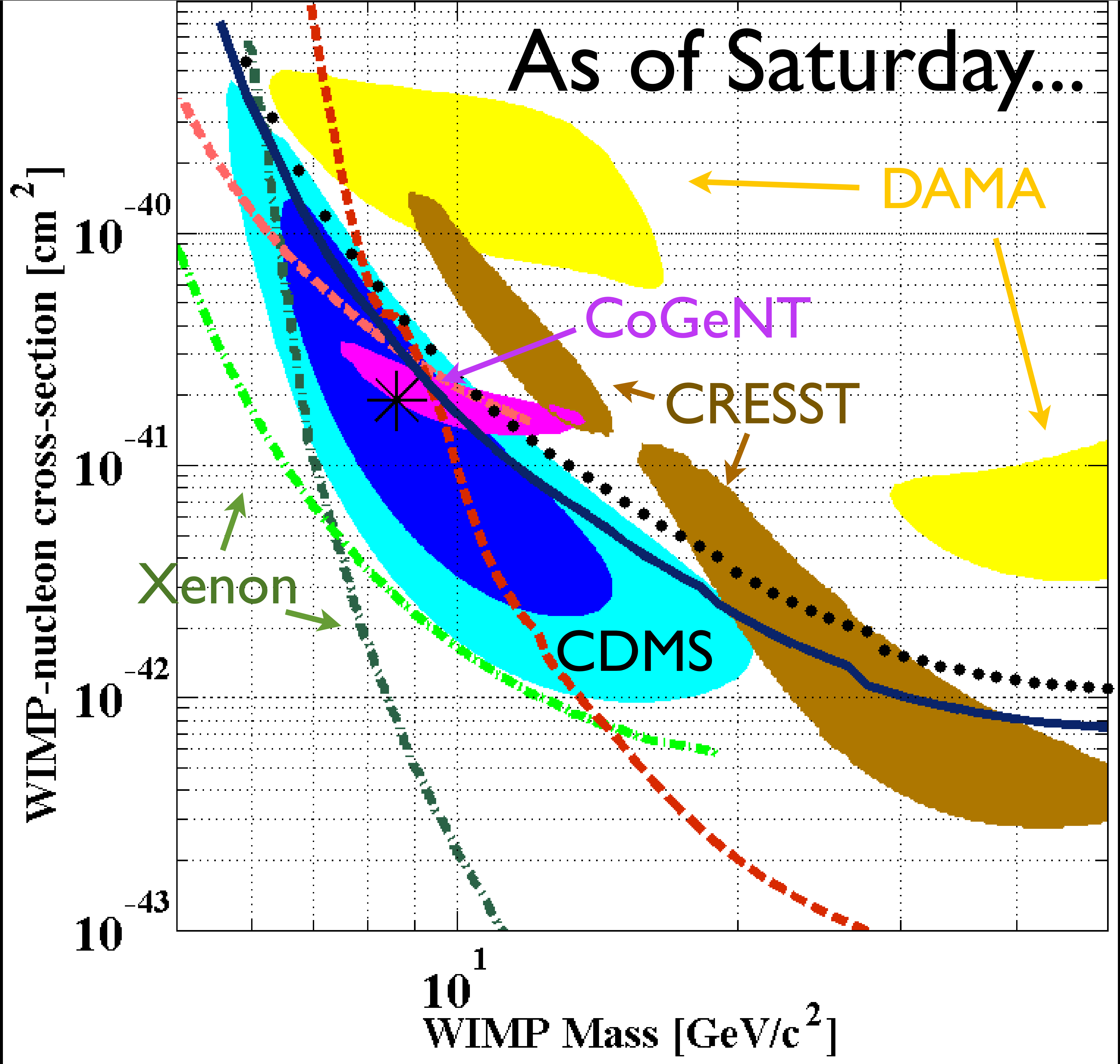


Fig. 13. The WIMP parameter space compatible with the CRESST results discussed here, using the background model described in the text, together with the exclusion limits from CDMS-II [12], XENON100 [13], and EDELWEISS-II [14], as well as the CRESST limit obtained in an earlier run [1]. Additionally, we show the 90% confidence regions favored by Co-

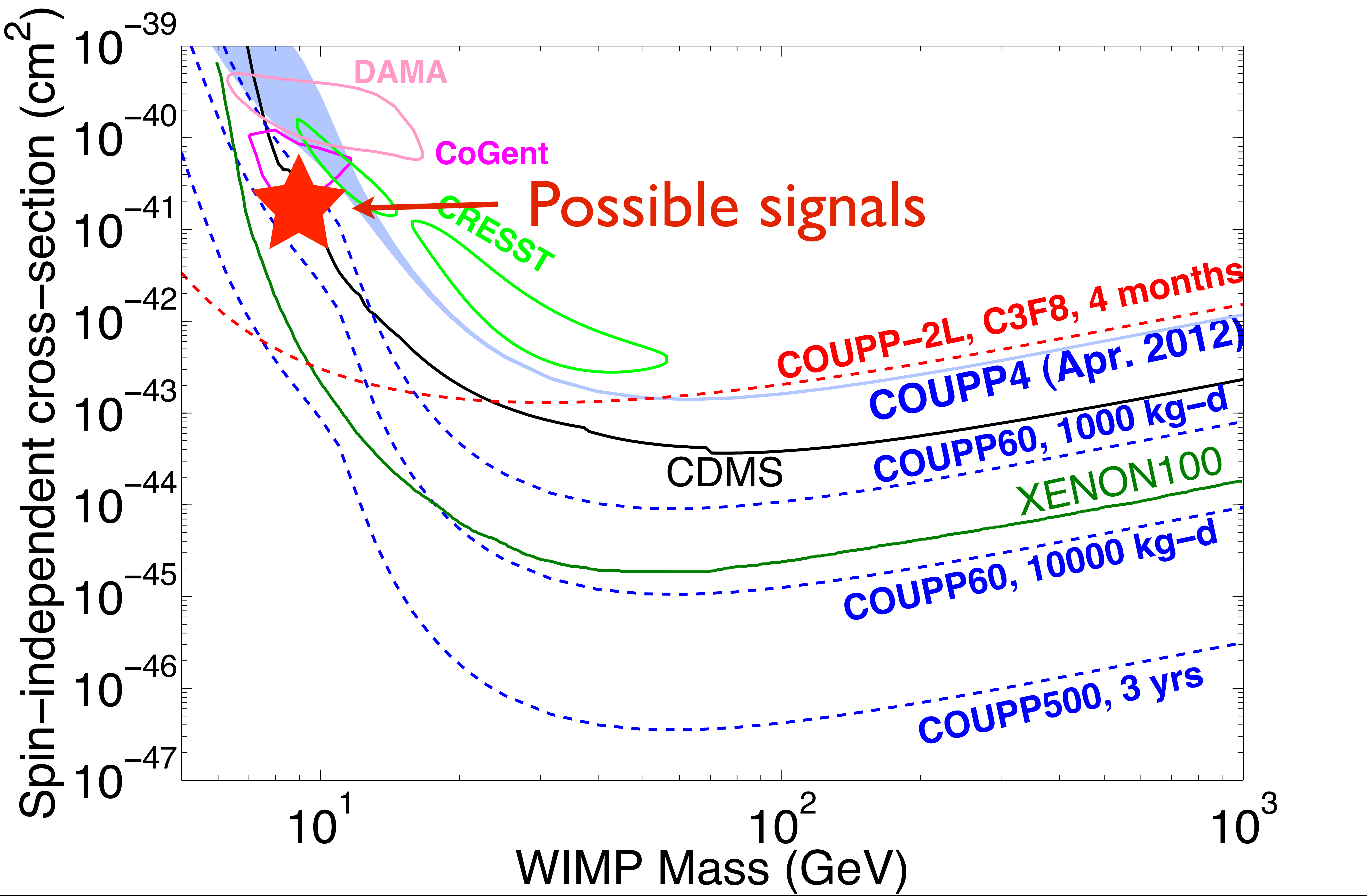


CRESST

- At APS on Saturday, CDMS (which has historically been the most conservative experiment, culturally speaking) announced a result that is consistent with a light WIMP hypothesis (best fit at 8.6 GeV, 1.9×10^{-41} cm^2)
- 3 candidate events over an estimated background of ~0.7. WIMP hypothesis fits with p-value of 68%, background only at 4.5%
- Nuclear recoil events (CDMS has discrimination, unlike DAMA or CoGeNT)


As of Saturday...
DAMA
CoGeNT
CRESST
Xenon
CDMS
WIMP-nucleon cross-section [cm^2]
10^-40
10^-41
10^-42
10^-43
10^1
WIMP Mass [GeV/c^2]

We'll see?


DAMA
CoGent
Possible signals
CRESST
COUPP–2L, C3F8, 4 months
COUPP4 (Apr. 2012)
COUPP60, 1000 kg–d
CDMS
XENON100
COUPP60, 10000 kg–d
COUPP500, 3 yrs
Spin–independent cross–section (cm^2)
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^1
10^2
10^3
WIMP Mass (GeV)

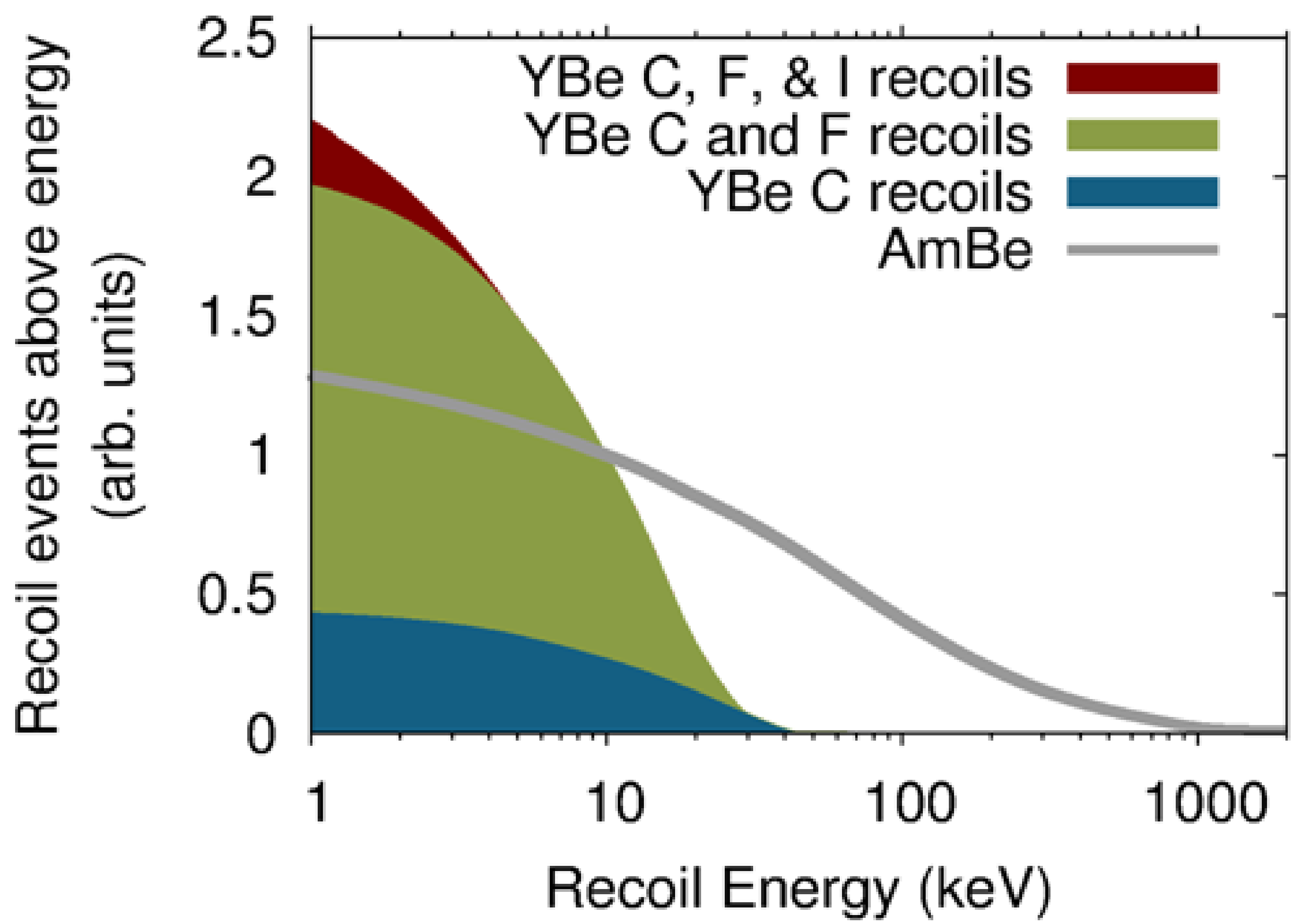
^{88}YBe (γ,n) neutron source

Mono-energetic 152 keV neutron source.

TABLE 3. Results of present measurements

E_γ (keV)	$\sigma(E_\gamma)$ (mb)
1674.7	0.88±0.16
1705.2	1.33±0.24
1724.9	1.10±0.20
1778.9	0.73±0.13
1836.0	0.47±0.09
2167.6	0.18±0.04

M. Fujishiro et al., Can. J. Phys. **60,** 1672 (1982).



WIMP-nucleon scattering

Spin-independent

Spin-dependent

$$\sigma_0 = \frac{4\mu^2}{\pi}\left[f_p N_p + f_n N_n\right]^2 + \frac{32 G_F^2 \mu^2}{\pi}\frac{J+1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

Nucleus	Z	Odd Nucleon	J	$\langle S_p\rangle$	$\langle S_n\rangle$	C_A^p/C_p	C_A^n/C_n
^{19}F	9	p	1/2	0.477	-0.004	9.10×10^{-1}	6.40×10^{-5}
^{23}Na	11	p	3/2	0.248	0.020	1.37×10^{-1}	8.89×10^{-4}
^{27}Al	13	p	5/2	-0.343	0.030	2.20×10^{-1}	1.68×10^{-3}
^{29}Si	14	n	1/2	-0.002	0.130	1.60×10^{-5}	6.76×10^{-2}
^{35}Cl	17	p	3/2	-0.083	0.004	1.53×10^{-2}	3.56×10^{-5}
^{39}K	19	p	3/2	-0.180	0.050	7.20×10^{-2}	5.56×10^{-3}
^{73}Ge	32	n	9/2	0.030	0.378	1.47×10^{-3}	2.33×10^{-1}
^{93}Nb	41	p	9/2	0.460	0.080	3.45×10^{-1}	1.04×10^{-2}
^{125}Te	52	n	1/2	0.001	0.287	4.00×10^{-6}	3.29×10^{-1}
^{127}I	53	p	5/2	0.309	0.075	1.78×10^{-1}	1.05×10^{-2}
^{129}Xe	54	n	1/2	0.028	0.359	3.14×10^{-3}	5.16×10^{-1}
^{131}Xe	54	n	3/2	-0.009	-0.227	1.80×10^{-4}	1.15×10^{-1}